EVALUATION OF BITUMINOUS MIXTURES USING THE GYRATORY TESTING MACHINE

AUGUST 1973 - NUMBER 18

BY

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JHRP

JOINT HIGHWAY RESEARCH PROJECT

PURDUE UNIVERSITY AND

INDIANA STATE HIGHWAY COMMISSION

Final Report

EVALUATION OF BITUMINOUS MIXTURES USING

THE GYRATORY TESTING MACHINE

TO:	J. F. McLaughlin, Director Joint Highway Research Project	August 29, 1973
		Project: C-36-6BB
FROM:	H. L. Michael, Associate Director Joint Highway Research Project	File: 2-4-28

The attached Final Report titled "Evaluation of Bituminous Mixtures Using the Gyratory Testing Machine" has been authored by Mr. Arun Kumar, Graduate Assistant in Research on our staff under the direction of Professor W. H. Goetz. Mr. Kumar also used the Report as his thesis for the M.S.C.E. degree.

The research reported was designed to evaluate the usefulness of the gyratory testing machine as a design tool and as an instrument for the evaluation of bituminous mixes. The research results indicate that the machine is sensitive enough to indicate changes in mixture properties caused by small variations in gradation and asphalt content and this can be successfully used to evaluate bituminous mixtures.

The Final Report is presented for acceptance as the results of the J.H.R.P. Study and as fulfillment of the objectives of the Study.

Respectfully submitted,

Harold L. Michael

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Arun Kumar
Graduate Assistant in Research

Joint Highway Research Project

Project No.: C-36-6BB

File No.: 2-4-28

Conducted By
Purdue University
In Cooperation With the
Indiana State Highway Commission

Purdue University
West Lafayette, Indiana
August 29, 1973

ACKNOWLEDGEMENTS

The author is grateful to the authorities of the Joint Highway Research Project of Purdue University and Dr. J. F. McLaughlin, Director, for its sponsorship of this research.

A most special thanks go to the author's major professor and advisor W. H. Goetz, for the time, support, and encouragement that he continually provided.

The author is thankful to Professor V. L. Anderson of the Department of Statistics for the meaningful discussions he had with him concerning the statistical analysis of the results. Thanks also go to Mr. R. D. Pavlovich for his constructive suggestions during the laboratory work.

The author expresses his appreciation to Dr. Bh. Subbaraju and Professor C. G. Swaminathan, Director and Deputy Director respectively, Central Road Research Institue, New Delhi, India, for the opportunity of pursuing the advanced degree.

Special thanks also go to the author's wife, Madhu, and their child, whose patience and understanding aided the successful completion of this investigation.

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ABSTRACT

Kumar, Arun. M.S.C.E., Purdue University, August, 1973. Evaluation of Bituminous Mixes Using the Gyratory Testing Machine. Major Professor: William H. Goetz.

This laboratory study was conducted to evaluate the usefulness of the gyratory testing machine as a design tool and as an instrument for the evaluation of bituminous mixes. Mixture variables included two types of aggregates, limestone and gravel, and a 60-70 penetration grade asphalt. The gradations specified by the Indiana State Highway Commission for HAC surface mixture type B were used to establish the job mix formula and the tolerance limits. The middle point of this selected gradation band was chosen for mixture design. Using this gradation, both limestone and gravel mixes were designed on the basis of their compaction and shear strain properties as obtained by means of the U.S. Corps of Engineers gyratory testing machine using the tentative ASTM testing method (1).

Mixture behavior was studied by observing changes in mixture properties under simulated traffic conditions using the GTM machine. Duplicate specimens were prepared (with designed percent asphalt) to construction density by compacting the mix in the gyratory testing machine using a technique that provides for simulated steel-wheel roller compaction. The

specimens were then subjected to simulated traffic densification using the gyratory testing machine. The densification was carried up to 1000 gyratory revolutions. The data were also utilized in evaluating the design procedure. The entire procedure of compaction and densification was applied to both limestone and gravel mixes made at the middle and extremes of the job mix formula by using the gradation tolerances and by varying asphalt content ± 0.3 percentage points from the designed value. The unit weight total mix, unit weight aggregate only, gyratory shear, gyratory stability index and gyratory compactibility index properties were calculated for each specimen. For clarity of presentation, these values were plotted against number of revolutions. Analysis of Variance and the Newman-Keuls Sequential Range Tests were carried out on the entire data.

The gyratory testing machine design method was evaluated based on the above results obtained by subjecting the designed mixes to the tolerance limits of ± 0.3 percentage points of asphalt. The results of the study indicated that for limestone mixtures (6.0 percent designed asphalt content) the increase in asphalt content from 6.0 percent to 6.3 percent did not produce any significant change in unit weight (total mix and aggregate only) but resulted in loss of stability. Reduction in asphalt content to 5.7 percent did not affect stability. Also, for these limestone mixtures, no appreciable change in shear values were observed due to variations in asphalt content. For gravel mixes (5.0 percent designed asphalt content) the increase in asphalt content from 5.0 to 5.3 percent resulted in decreased shear values and loss in stability with no appreciable gains in unit weight (total mix and aggregate only). Use of 4.7 percent asphalt did not produce any appreciable changes except a small increase in stability at 1000 revolutions of simulated traffic densification. In short, the designed percent asphalt content for both limestone and gravel mixes seemed justified and hence it was concluded that the tentative ASTM testing method utilizing the gyratory testing machine can be used successfully to design bituminous mixes.

The simulated field compaction and simulated traffic densification test results were also utilized for the evaluation of bituminous mixes. This evaluation consisted mainly of two factors; first, to study the influence of simulated traffic densification on the mixture properties; and second, to examine the job mix formula and the tolerance limits.

Influence of simulated traffic densification on the mixture properties study, indicated that for both limestone and gravel mixes, gradation and number of revolutions significantly affected all the mixture properties(unit weight total mix, unit weight aggregate only, gyratory shear, gyratory stability index and gyratory compactibility index). The only exception was that the gyratory shear value did not change significantly due to changes in limestone mixture gradation. Variations in asphalt content did not significantly affect the unit weight (aggregate only) and gyratory shear values of the limestone mixtures (up to 500 revolutions). Unit weight (aggregate only) became significant with further increase in number of revolutions. In the case of gravel mixtures, no significant differences were observed in unit weight (aggregate only) and gyratory compactibility index properties (up to 500 revolutions) only; however, the gyratory compactibility index value became significant when tested up to 1000 revolutions. This indicated that the gyratory testing machine can predict the mixture behavior at any level of traffic densitification for both limestone and gravel types of mixes.

From the Job mix formula and the tolerance limits study it was observed that for limestone mixtures, the use of gradation C instead of gradation B resulted in significant gain in unit weight (total mix and aggregate only) with loss in stability. On the other hand, the use of gradation A produced a loss in unit weight (total mix and aggregate only) without any gain in stability. Use of 6.3 percent asphalt content instead of 6.0 percent resulted in loss in stability at higher densification effort without any gain in other properties. When 5.7 percent asphalt content was used, it resulted in loss in unit weight (total mix) without any gain in other properties.

For gravel mixtures it was observed that the use of the finer side of the designed gradation resulted in loss in stability and loss in shear strength without any appreciable gain in unit weight (total mix and aggregate only). Use of the coarser side of the designed gradation at low densifying effort resulted in loss in unit weight (total mix and aggregate only) without any appreciable increase in shear strength, but the stability of the mixture improved. Increase in densifying effort resulted in gain in unit weight (aggregate only) with reduction in shear strength. The stability value remained unaffected. Use of asphalt on the higher side of the designed value did not improve the unit weight (total mix and aggregate only) values but resulted in loss in shear strength and loss in stability. When the quantity of asphalt used was on the lower side of the designed value, no appreciable loss in unit weight (total mix and aggregate only) was observed but the shear strength and stability of the mixture was improved at low densification level. The shear strength value was reduced with increased densification effort.

The above analysis as applied to both limestone and gravel mixes indicated that the gyratory testing machine is sensitive enough to study the changes in mixture properties caused by small variations in gradation and asphalt content. Thus, the successful use of the gyratory testing machine in evaluating bituminous mixes was demonstrated.

INTRODUCTION

One of the main objectives of bituminous paving mixture design is to select a bitumen-aggregate combination such that the mix so obtained will be as durable as possible and yet be stable. To accomplish this objective, one of the critical aspects is to be able to produce in the laboratory a compacted specimen that is truly representative of the mixture as it will be in service on the road. Most of the present design procedures utilize a constant level of compactive effort which is intended to produce densities (at designed asphalt content) comparable to those occurring in the field after a period of traffic densification. This approach may be open to question because a given level of laboratory compaction cannot be considered to produce specimens representative of the density of all mixtures and service conditions after a specified period of time.

It would be logical to compact specimens in the laboratory to a density which is representative of the field compacted density at the time of construction and then to densify these by simulating the effects of traffic. It is desirable to measure stability continuously during this process. By this procedure it should be possible to select the maximum asphalt content that may be used under a variety of service conditions without excessive loss in stability. The gyratory testing machine can be used in this way for bituminous mixture design.

Based on the above reasoning it seemed useful to undertake a laboratory study to design and evaluate bituminous mixtures using the gyratory testing machine. Accordingly, a mixture type commonly used in Indiana was selected and designed for the optimum asphalt content. The designed asphalt content and the selected gradation were subjected to permitted job-mix tolerances. Specimens covering this range of composition were prepared and tested under simulated field compaction and simulated traffic densification conditions.

It was contemplated that the results obtained would help in studying the following factors:

1) Evaluation of the gyratory testing machine design method.
2) Influence of simulated traffic densification on the mixture properties. The purpose is to study the capability of the gyratory testing machine to evaluate bituminous mixes at any specified densification effort. Positive results may lead to an estimation of pavement life.
3) Job mix formula and tolerance limits. The sensitivity of the gyratory testing machine when used to study the job mix formula tolerances was investigated. Favorable results may help in modifying specifications to suit field conditions.

The data obtained from simulated field compaction and simulated traffic densification testing were used in the evaluation of the gyratory testing machine testing method. The same data were also utilized in the bituminous mixture evaluation which consisted mainly of two factors; first, to study the influence of simulated traffic densification on mixture properties and second, to examine the job mix formula and the tolerance limits.

REVIEW OF LITERATURE

The Texas Highway Department started a research program in 1939 on the design and control of bituminous mixes. It was felt that the molding method for the design should simulate road conditions. Therefore, one of the first problems was to find a procedure for molding the asphaltic concrete test specimens.

Ortolani and Sandberg (2) state the criteria that was set up for the molding method:

> "First, the method must be equally adaptable to the field control of the mix as to the design. An excellent but lengthy design procedure would be useless in the field as a control test. Second, the method should yield essentially the same density, or voids ratio, as that obtained in the finished pavement. Since the life of the pavement must be taken into account, and realizing that density increases to a maximum with time and traffic, the desired density to be obtained with any molding procedure should approximate that of the pavement after sometime in the road. This final pavement density is referred to as ultimate density and is the goal of any compaction method. The aggregate will break down under field compaction methods, thus, a third requirement of the molding method was to approximate as nearly as possible, the aggregate degradation obtained under field conditions."

Based on these, numerous machines were constructed, tested in the laboratory and rejected for one reason or another. The gyratory molding machine was the ninth such machine to be investigated and was found to be satisfactory.

The Waterways Experiment Station developed the gyratory testing machine, based on the compaction method used by the Texas Highway Department, in an effort to develop improved procedures for the design and control of hot-mix bituminous pavements. Some of the capabilities of the machine as mentioned in Technical Report No. 3-595 (3) are as follows:

1) It produces high densities that develop under channelized traffic of heavy wheel loads.

2) It produces specimens with stress-strain characteristics similar to those of actual pavement samples of equal density and bitumen content.

3) It can predict the number of load applications a paving mixture can withstand before failure.

4) It can predict the design bitumen content independently of voids criteria.

5) It can provide a more positive and faster plant control test.

Following are the concluding remarks made in this Technical Report on the use of the gyratory testing machine.

> "The principle of the gyratory machine for selecting design bitumen content and for use in control testing is considered sound. It must be recognized, however, that the machine is not capable of predicting a correct design bitumen content unless the proper compaction effort is selected, i.e. an effort that will develop densities equal to ultimate pavement densities."

In order to arrive at the design bitumen content, it is necessary that the anticipated prototype density should be reproduced in the laboratory. The prepared sample should also have stress-strain properties comparable to the prototype. McRae and Foster (4) in describing the utility of the gyratory testing machine write:

> "The gyratory testing machine is not only a machine to compact realistic specimens from the standpoint of density and stress-strain characteristics but it also may be a machine which will automatically indicate the plastic conditions of the sample and will indicate the point at which the sample becomes overplastic. It is thus a tool for directly determining the optimum bitumen content."

In 1963, Busching (5) used this machine to compact bituminous mixtures in the laboratory in an attempt to simulate the compaction which would be imparted by construction and traffic densification. The study also consisted of stability measurements of specimens compacted under varying levels of simulated construction and traffic densification. The compactive effort was varied by changing ram pressure and number of gyratory revolutions as well as type of operation in the gyratory testing machine. Stability measurements were made using the Hveem Stabilometer.

The results of the study indicated that an increase in initial compaction pressure and number of revolutions increased the initial stability. For the two mixtures studied (dense-graded and open-graded), the results showed that all levels of secondary compaction, whether imposed by a decreased compaction pressure and a greater number of revolutions or by increased compaction pressure, produced additional specimen compaction. This indicates that an increase in initial compaction will decrease the secondary compaction which can be applied before loss in stability occurs.

All five main factors studied in the laboratory played a significant role in affecting specimen compaction. Their importance in order were: secondary revolutions, initial pressure, secondary pressure, initial revolutions and gradation.

In 1964, Hughes (6) conducted a laboratory study to determine a procedure for use of the gyratory testing machine as a device to apply a loading action to bituminous concrete specimens that would produce effects similar to the rutting and shoving types of failure created in pavements by traffic action. He varied ram pressure, air roller pressure and gyration angle with a view to determining their individual effects upon laboratory specimens. He then selected one combination of the gyratory testing machine variables to represent simulated traffic action and performed tests on mixtures of several aggregate gradations at a varying asphalt content.

The results showed that the use of the gyratory testing machine as a traffic simulating device produced changes in Hveem Stability and bulk density of laboratory specimens which were thought to be characteristic of property changes that may occur in actual pavements. The study also showed the range in magnitude of individual gyratory machine variables that might be utilized best for a traffic testing procedure. The simulated traffic testing of mixtures of different aggregate gradations at the same asphalt content showed that a difference in performance could be expected from them.

It was concluded that the gyratory testing machine can be used successfully as a traffic simulating device for the purpose of producing effects similar to rutting and shoving types of failure created in pavements by traffic action.

In 1966, Ruth and Schaub (7) initiated a study for the purpose of simulating in the laboratory the rate of densification produced in the field by steel-wheel compaction equipment. The results obtained in the study demonstrated that the gyratory testing machine simulation of field compaction of asphaltic concrete mixtures is both feasible and practical. The use of an air roller equipped gyratory testing machine set at a 3-degree angle of gyration, 15 psi air roller pressure and 100 psi ram pressure successfully simulated the rate of densification of various mixtures compacted in the field by a 12-ton steel-wheel break down roller. The use of gyratory shear values as a measure of relative stability was felt to be promising. A gyratory shear value of 30 psi for the test conditions used in the study was thought to be useful in establishing a minimum stability criterion for compaction.

Then, in 1968, Ruth & Schaub (8) proposed a method for estimating the design asphalt content for bituminous mixtures which is as follows:

"Initial hot mix compaction was performed using 12 revolutions of the GTM with settings of a 3^{o} angle, 100 psi ram pressure and 15 psi air roller pressure. After initial compaction, the sample was subjected to further densification by the GTM under conditions of 140^{o}F temperature, 2^{o} angle, 100 psi ram pressure and 20 psi air roller pressure. Densification was extended to 200 revolutions. The design asphalt content was chosen as that which produced a sample having a gyratory shear value of 27.0 after densification."

Later, Potts (9) investigated the feasibility of equating the number of revolutions of the gyratory testing machine to the number of applications of equivalent wheel loads. He used bulk density as the common factor to determine the equivalency between field and laboratory densification of bituminous mixtures. Using field and laboratory results, Potts developed an equation to predict field and laboratory density values using the traffic data in terms of accumulative number of equivalent 5000 lb. wheel loads and the gyratory compaction data in terms of number of revolutions of the gyratory testing machine, respectively.

The above review of literature shows that the gyratory testing machine can be used for designing bituminous mixtures. The simulation of field compaction and traffic densification is both feasible and practical in the laboratory through the use of this machine.

MATERIALS AND MIXTURE PREPARATION

In this section, the materials used for this investigation and their source and properties are given; the basis of selection of aggregate gradation is presented and the procedure used for the preparation of bituminous mixtures is described. The presentation is in the following order:

Aggregate

Asphalt

Aggregate gradation

Mixture preparation

Aggregate

Two types of aggregates, limestone and gravel, commonly used by the Indiana State Highway Commission in their hot asphaltic concrete (HAC) surface mixture type B, were used in the study. The sources from which they were obtained were:

1.	Limestone	Swayzee, Indiana
2.	Limestone Filler	Swayzee, Indiana
3.	Gravel	West Lafayette, Indiana
4.	Natural Sand	West Lafayette, Indiana

The aggregates were first dried to a constant weight and then sieved into desired sieve sizes. Specific gravity and the absorption tests were conducted on these materials according to ASTM methods C 127 and C 128. The results of these tests are shown in Table 1. All results are the average of three determinations.

Asphalt

A 60-70 penetration grade asphalt cement was used throughout the study. It was obtained from the Asphalt Materials Company, Indianapolis, Indiana.

Table 2 presents the results of the tests on this asphalt.

Aggregate Gradation

For this investigation, a job mix formula based on the specifications of the Indiana State Highway Commission (10) HAC (hot asphaltic concrete) surface mixture type B was selected.

For type B surface mixtures, a typical job mix formula issued by the Indiana State Highway Commission contains the following:

1) Coarse aggregate No. 11 is specified.
2) Fine aggregate No. 14-2 (or No. 17) is specified.
3) Percent of aggregate passing the No. 6 sieve is specified to be 47 ± 3.
4) Limits of the percent passing the No. 200 sieve are specified to be 0 to 3.

Table 1. Results of Tests on Aggregates

Material		Bulk Specific Gravity	Bulk Specific Gravity (Saturated Surface-Dry Basis)	Apparent Specific Gravity	Percent Absorption
Limestone	Coarse Aggregate (Retained #6 Sieve)	2.52	2.58	2.69	2.47
	Fine Aggregate (Passing #6 Sieve)	2.41	2.49	2.62	3.34
Gravel	Coarse Aggregate (Retained #6 Sieve)	2.61	2.66	2.75	1.85
	Fine Aggregate (Passing #6 Sieve)	2.49	2.53	2.60	1.71

Table 2. Results of Tests on Asphalt Cement

		Test Method
Solubility in Carbon Tetrachloride, %	99.85	ASTM D4
Penetration, 100 grams, 5 sec., 77°F	67	ASTM D5
Loss on Heating, 50 grams, 5 hr., 325°F, %	0.04	ASTM D6
Penetration of Residue, % of Original	84	ASTM D5
Specific Gravity at 77°F	1.019	ASTM D70
Flash Point, Cleveland Open Cup, °F	400^+	ASTM D92
Ductility at 77°F, 5 cm/min., cm	100^+	ASTM D113
Kinematic Viscosity at 275°F, cSt	456	ASTM D2170
Absolute Viscosity at 140°F, poises	2426	ASTM D2171
Spot Test	Negative	AASHO T 102

Table 3 and Figure 1 present the gradation limits specified for coarse aggregate No. 11, fine aggregates No. 14-2 & No. 17, and surface mixture type B.

To obtain the widest possible gradation band feasible within the type B surface mixture specifications, the gradation ranges for all possible blends using upper and lower limits of the coarse and fine aggregate sizes were calculated. These are presented in Tables 4 and 5. Table 6 summarizes the limits of blends of coarse aggregate No. 11 with fine aggregate No. 14-2 and with fine aggregate No. 17. In Figure 2, these are compared with the gradation limits of the surface mixture type B. The widest possible gradation band satisfying surface mixture type B was selected for this investigation since this can be the maximum variation within the job mix formula and the permissible tolerances. Table 7 and Figure 3 present the lower limit (gradation A), the middle point (gradation B) and the upper limit (gradation C) of the selected gradation band.

Mixture Preparation

The bituminous mixture preparation procedure described in this section was followed for both mixture design and mixture evaluation.

After drying and sieving, the aggregates were batched for each specimen by component fractions in accordance with the accumulative batch weight formula (based on the selected aggregate gradation). This was accomplished by weighing

Table 3. Gradations as Specified by Indiana State Highway Commission

U.S. Sieve Size	Total Percent Passing			
	Coarse Agg.	Fine Agg.		Surface Mixture Type B
	Size No. 11	Size No. 14-2	Size No. 17	
1/2"	100			100
3/8"	75-95	100		80-97
#4	5-20	98-100	100	40-60
#6	--	--	--	35-55
#8	0-5	75-95	90-100	30-48
#16	--	50-75	55-85	18-35
#30	--	20-53	20-55	9-24
#50	--	6-25	5-35	3-13
#100	--	1-17	1-15	0-8
#200	0-2	0-3	0-5	0-3

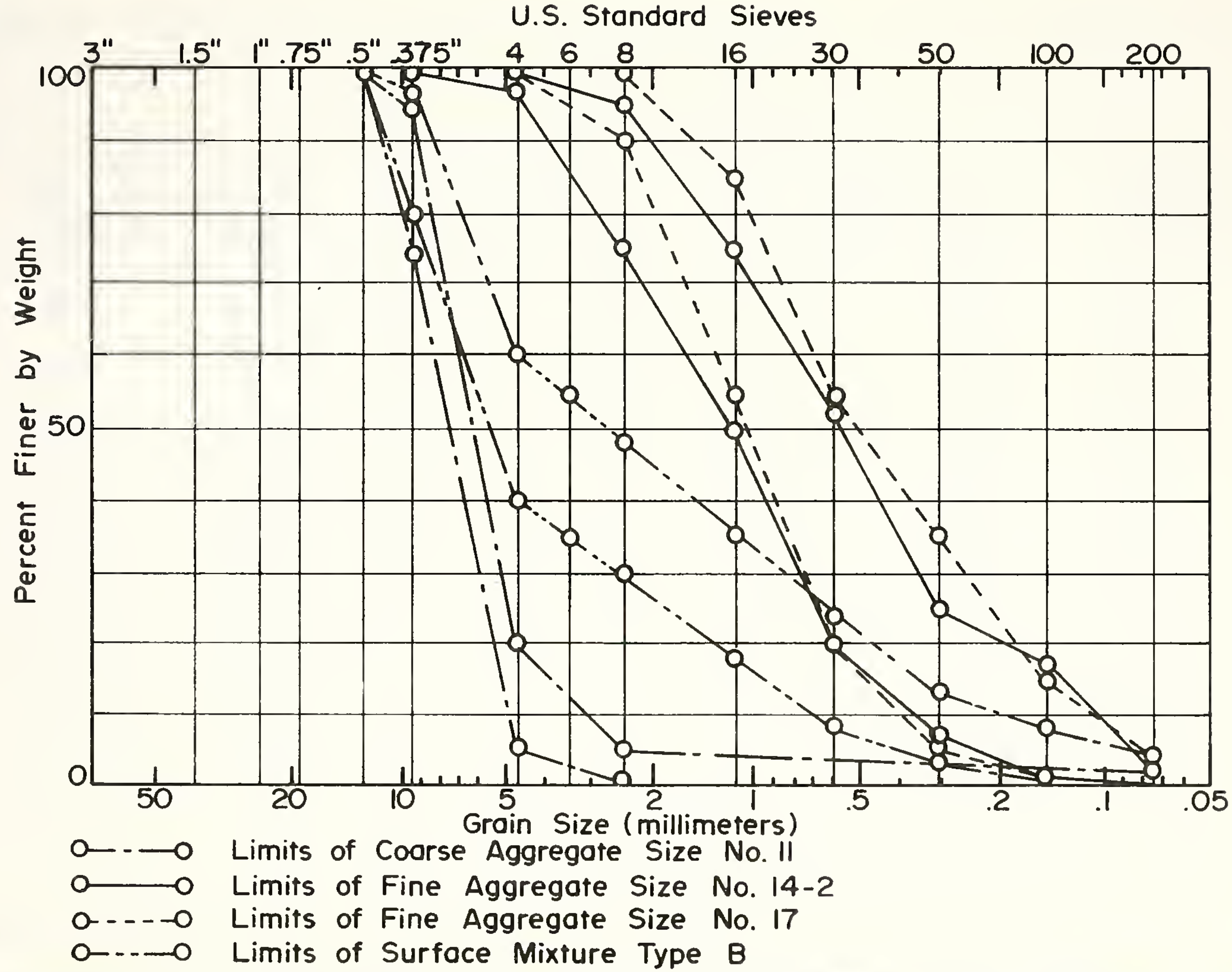


FIGURE 1 - GRADATIONS AS SPECIFIED BY INDIANA STATE HIGHWAY COMMISSION.

Table 4. Master Limits for Blends of Coarse Aggregate No. 11 and Fine Aggregate No. 14-2

U.S. Sieve Size	Total Percent Passing							
	Coarse Agg. #11 UL, Fine Agg. #14-2 UL, % Passing Sieve #6		Coarse Agg. #11 LL, Fine Agg. #14-2 LL, % Passing Sieve #6		Coarse Agg. #11 LL, Fine Agg. #14-2 UL, % Passing Sieve #6		Coarse Agg. #11 UL, Fine Agg. #14-2 LL, % Passing Sieve #6	
	44	50	44	50	44	50	44	50
1/2"	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
3/8"	96.9	97.1	87.4	89.1	85.9	87.5	97.0	97.5
#4	49.2	54.8	51.0	57.6	46.5	52.5	52.6	59.0
#6	44.0	50.0	44.0	50.0	44.0	50.0	44.0	50.0
#8	37.9	44.1	38.1	42.4	41.5	47.5	34.4	40.0
#16	30.3	35.1	24.8	28.2	32.8	37.5	23.6	27.2
#30	21.9	25.4	9.9	11.3	23.2	26.5	10.7	12.0
#50	11.3	12.9	3.0	3.4	10.9	12.5	4.5	4.7
#100	8.1	9.1	0.5	0.5	7.4	8.5	2.1	2.0
#200	2.4	2.4	0.0	0.0	1.3	1.5	1.2	1.0

UL - Upper Limit, refers to finer limit of the gradation band

LL - Lower Limit, refers to coarser limit of the gradation band

Table 5. Master Limits for Blends of Coarse Aggregate No. 11 and Fine Aggregate No. 17

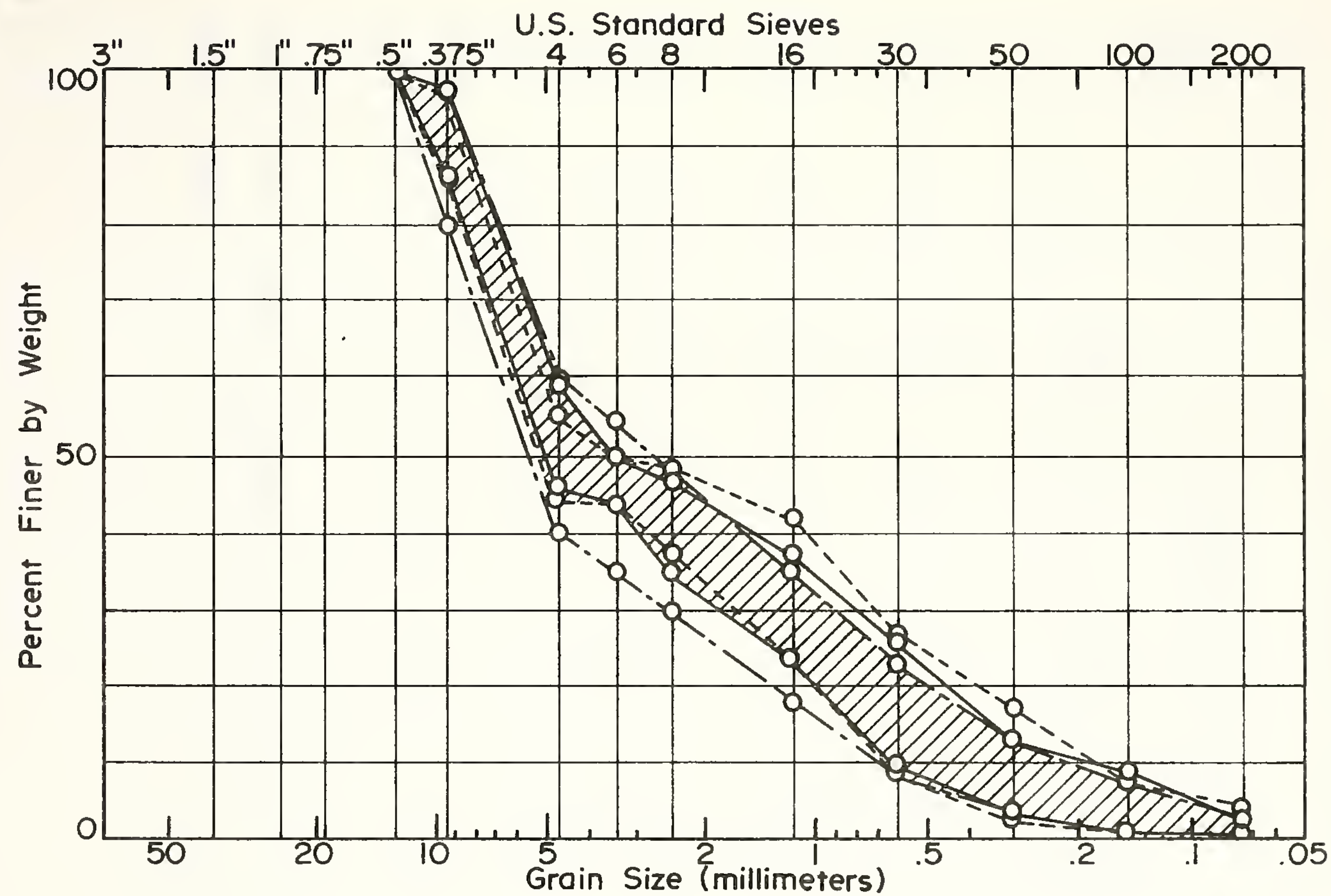
U.S. Sieve Size	Total Percent Passing							
	Coarse Agg. #11 UL, Fine Agg. #17 UL, % Passing Sieve #6		Coarse Agg. #11 LL, Fine Agg. #17 LL, % Passing Sieve #6		Coarse Agg. #11 LL, Fine Agg. #17 UL, % Passing Sieve #6		Coarse Agg. #11 UL, Fine Agg. #17 LL, % Passing Sieve #6	
	44	50	44	50	44	50	44	50
1/2"	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
3/8"	96.8	97.1	86.3	87.9	85.7	87.2	96.9	97.3
#4	48.5	54.0	47.9	54.0	45.7	51.5	50.2	56.1
#6	44.0	50.0	44.0	50.0	44.0	50.0	44.0	50.0
#8	38.8	45.4	40.7	46.4	42.9	49.0	37.1	43.3
#16	33.2	38.7	24.9	28.4	36.5	41.6	23.6	27.3
#30	22.2	25.7	9.0	10.3	23.6	26.9	10.1	11.2
#50	14.8	16.8	2.3	2.6	15.0	17.1	4.1	4.2
#100	7.2	8.1	0.5	0.5	6.4	7.3	2.3	2.1
#200	3.1	3.2	0.0	0.0	2.1	2.4	1.2	0.6

UL - Upper Limit, refers to finer limit of the gradation band

LL - Lower Limit, refers to coarser limit of the gradation band

Table 6. Gradation Limits Based on Job Mix Formula

U.S. Sieve Size	Total Percent Passing			
	Limits of Coarse Agg #11 and Fine Agg #14-2 Blend	Limits of Coarse Agg #11 and Fine Agg #17 Blend	Specification Limits of Surface Type B Mix	Selected Gradation Limits
1/2"	100	100	100	100
3/8"	85.9-97.5	85.7-97.3	80-97	85-97
#4	46.5-59.0	45.7-56.1	40-60	45-59
#6	44.0-50.0	44.0-50.0	35-55	44-50
#8	34.4-47.5	37.1-49.0	30-48	34-48
#16	23.6-37.5	23.6-41.6	18-35	23-35
#30	9.9-26.5	9.0-26.9	9-24	9-24
#50	3.0-12.9	2.3-17.1	3-13	3-13
#100	0.5-9.1	0.5-8.1	0-8	0-8
#200	0.0-2.4	0.0-3.2	0-3	0-3



Limits of Coarse Aggregate No. 11 and Fine Aggregate No. 14-2 Blend
Limits of Coarse Aggregate No. 11 and Fine Aggregate No. 17 Blend
Limits of Surface Mixture Type B
Selected Gradation Band

FIGURE 2 -GRADATION LIMITS BASED ON THE JOB MIX FORMULA AND THE TOLERANCE LIMITS.

Table 7. Selected Aggregate Gradations

U.S. Sieve Size	Total Percent Passing		
	A Lower Limit	B Middle Point	C Upper Limit
1/2"	100	100	100
3/4"	85	91	97
#4	45	52	59
#6	44	47	50
#8	34	41	48
#16	23	29	35
#30	9	16.5	24
#50	3	8	13
#100	0	4	8
#200	0	1.5	3

Lower Limit - Refers to Coarser Limit of the Gradation Band

Upper Limit - Refers to Finer Limit of the Gradation Band

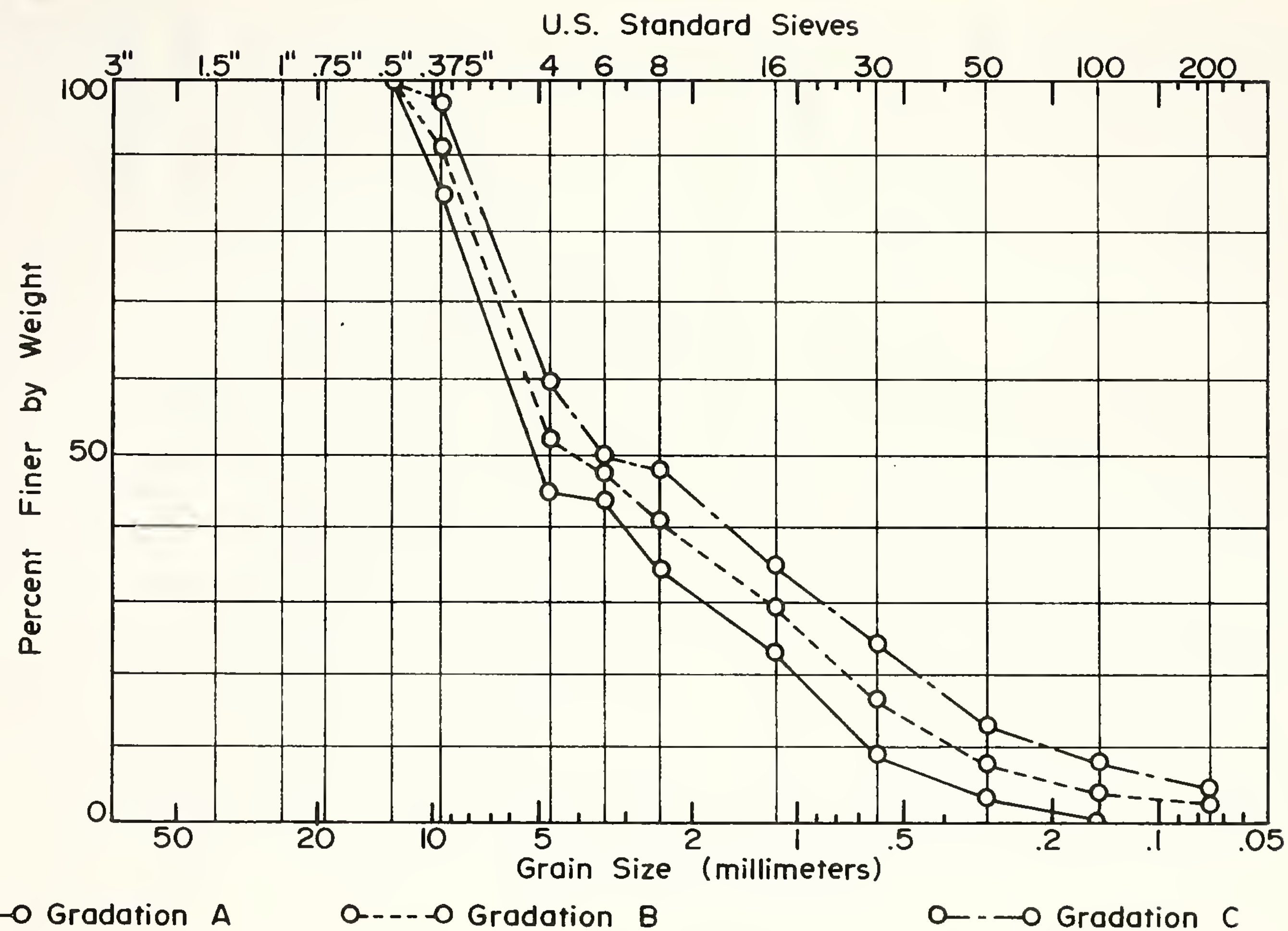


FIGURE 3 - SELECTED AGGREGATE GRADATIONS.

the cold dried aggregates on a Toledo scale sensitive to one gram. The batch weight was 1100 grams.

Each individual batch of aggregate was thoroughly mixed, placed in the oven and heated to 325 $\pm$ 5^{o}F. The asphalt was heated separately to 300 $\pm$ 5^{o}F. (According to the ASTM testing method (1), which was followed to obtain mixture properties for bituminous mixture design, the asphalt temperature based on viscosity came out to be 325^{o}F and for aggregate, 350^{o}F. The simulated field compaction procedure used (8) specifies that both 85-100 penetration grade asphalt and the aggregate should be heated to 300^{o}F. No temperature is specified for 60-70 penetration grade asphalt. Since the mixture preparation procedure used for both was to be the same, it was decided to heat asphalt to 300^{o}F and aggregate to 325^{o}F.) To avoid excessive loss of heat during mixing, the mixing bowl and paddle were also heated to 275 $\pm$ 5^{o}F. The hot aggregate was transferred to the mixing bowl and a crater was formed at the center. The bowl was then placed on the scale, tared and the desired amount of asphalt (to the nearest one tenth of a gram) was added. The aggregate and the asphalt were mixed in the Hobart electric mixer (Model N-50) for two minutes. The batch was then ready for compaction.

BITUMINOUS MIXTURE DESIGN

The gyratory testing machine was used for compaction and testing. This machine, developed by the Waterways Experiment Station, Vicksburg, Mississippi, is based on a compaction technique devised by the Texas Highway Department. Figures 4 and 5 show the gyratory testing machine and a schematic view of the gyratory mechanism, respectively. A detailed description of the machine can be found in the Gyratory Testing Machine Manual (11). In the rest of this report the abbreviated term GTM will be used for gyratory testing machine.

This section describes the tentative ASTM testing method (1) followed to obtain the mixture properties (unit weight total mix, unit weight aggregate only, gyratory elasto-plastic index, gyratory stability index and gyratory compactibility index) and the interpretation of them used to obtain the design asphalt content. (Since the ASTM testing method does not indicate how to use these properties for mixture design, the author has made his own interpretation of the data for this purpose.) The sequence of presentation is as follows:

The ASTM testing method

Presentation of results and the mixture design

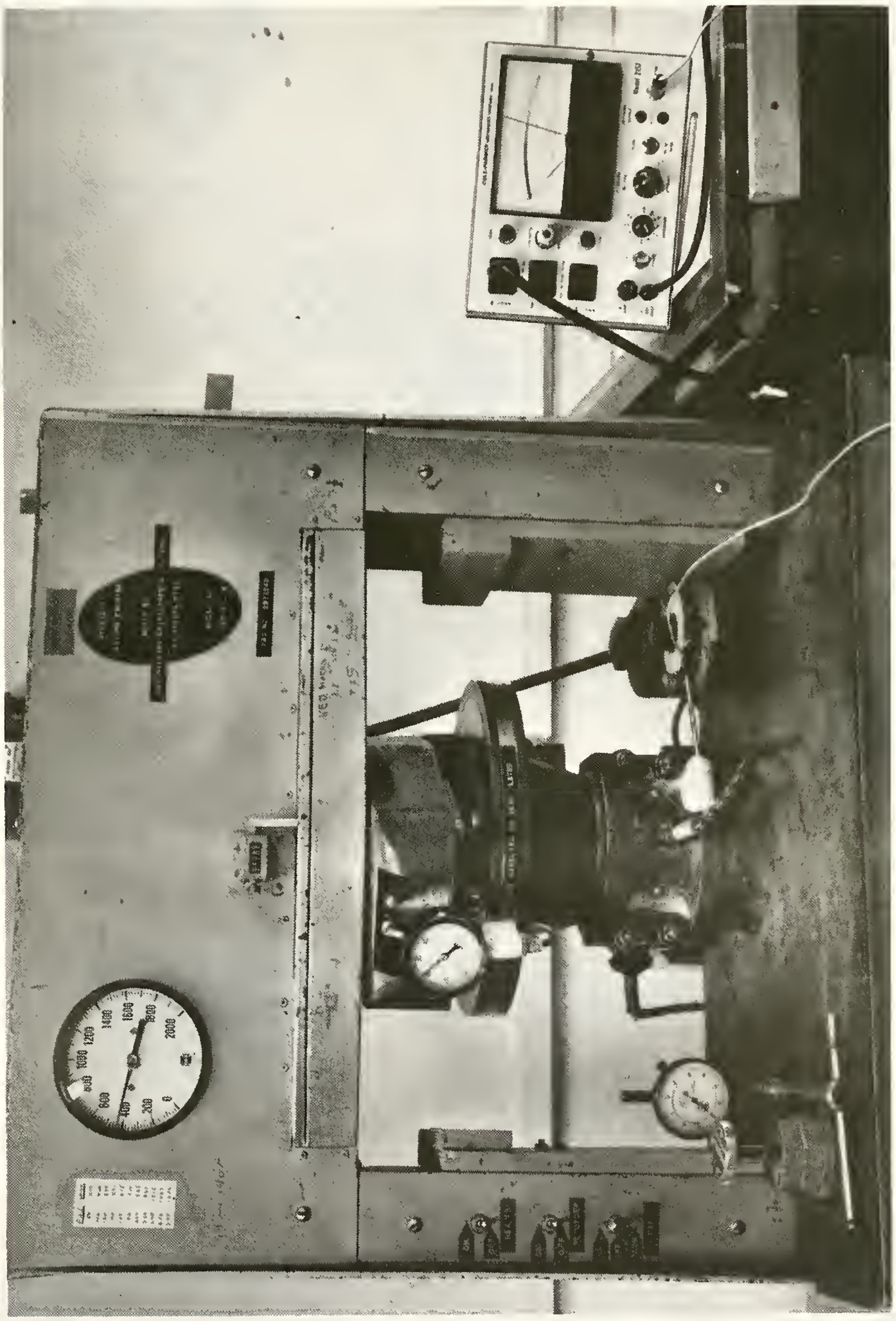


FIGURE 4 -THE GYRATORY TESTING MACHINE.

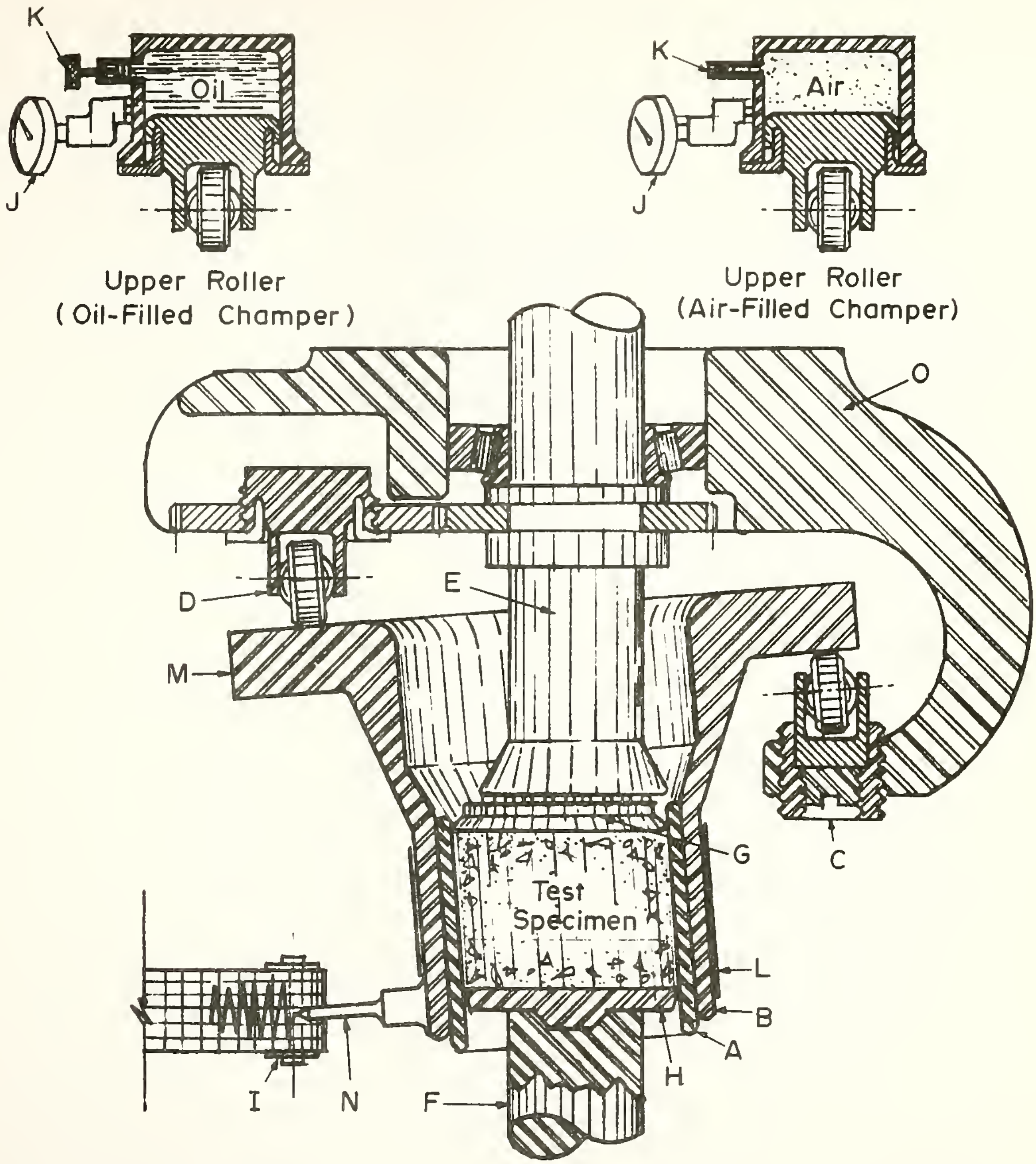


FIGURE 5 - SCHEMATIC SECTION OF GYRATING MECHANISM

Key to details of Figure 5

A. Specimen mold

B. Mold chuck

C. Lower roller

D. Upper roller

E. Upper ram shaft

F. Lower ram shaft

G. Upper head

H. Lower head

I. Gyrograph

J. Pressure gauge

K. Filling valve

L. Heating element

M. Chuck flange

N. Recorder pen

O. Roller carriage

The ASTM Testing Method

The prepared mixture (as described earlier under the heading 'Mixture Preparation') was compacted using the following procedure:

The GTM fixed roller was installed in the roller carriage at the upper roller position. The machine settings were then made by adjusting the gyratory angle at 1 degree and the vertical pressure at 200 psi. A trial batch of mix was used in setting the vertical pressure and the initial gyratory angle. The GTM heater, set at 140^{o}F, was switched on one hour before starting the specimen compaction. To avoid loss of heat during compaction, the mold and the base plate were preheated to 250^{o}F.

The heated mold, base plate and a paper disc were placed on the carrying tray. The bituminous mixture contained in the mixing bowl was then transferred into the mold with a spoon in a manner to avoid hand troweling or tamping, and a paper disc was placed on top of the mixture. With the help of the carrying tray, the mold containing the mixture was placed in the GTM and the vertical pressure was applied. After clamping the mold in the mold chuck, the gyrograph recorder (Figure 6) was started and the height of the specimen was noted at three roller positions 120^{o} apart. This was done in order to obtain the average initial specimen height. The roller carriage was then actuated and continued until 29 revolutions had been applied. At the completion of 29 revolutions the carriage was stopped and the height readings

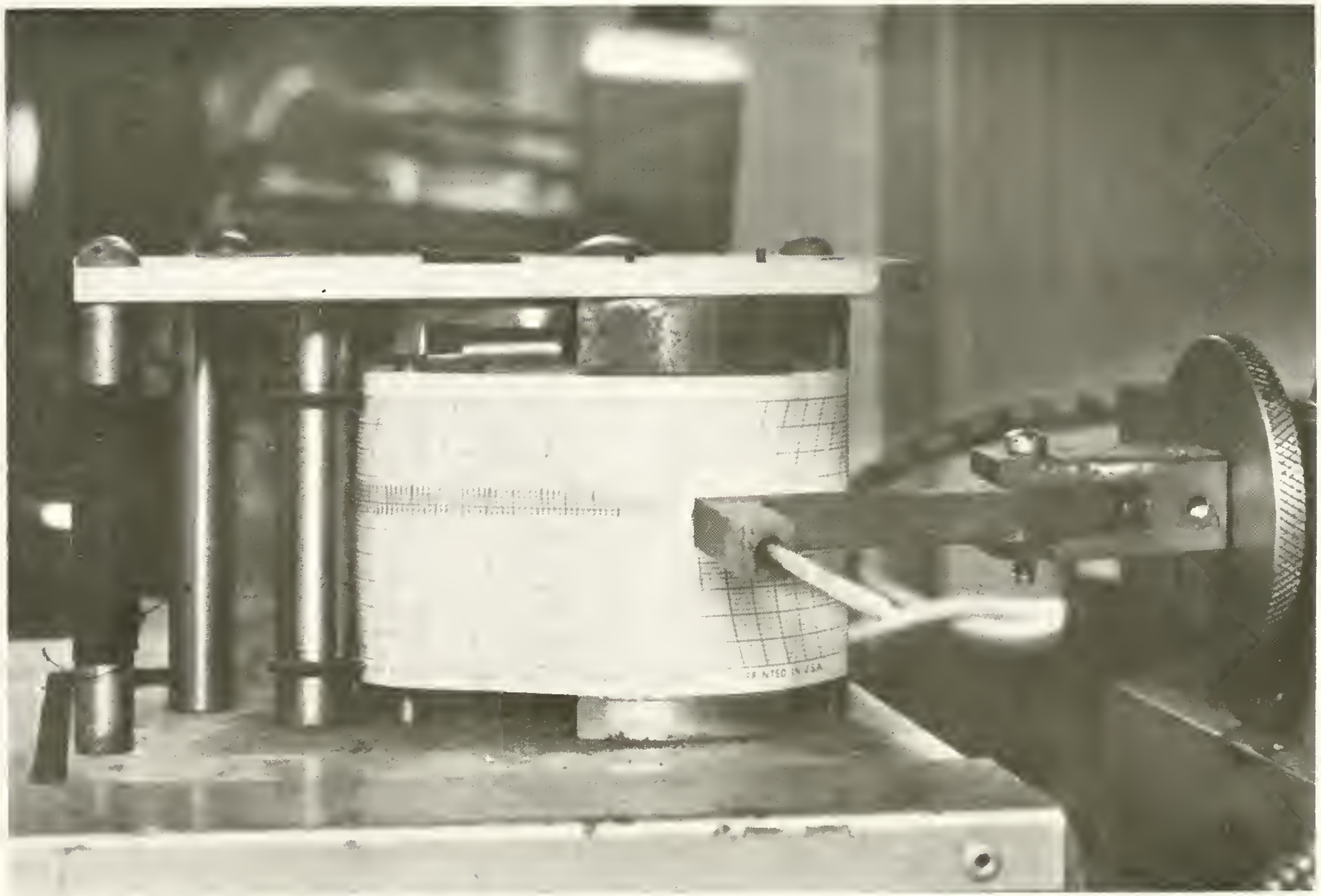


FIGURE 6 -THE GYROGRAPH RECORDER .

were recorded again at the three roller positions, thus completing 30 revolutions. The roller carriage was started immediately and additional revolutions were applied until a total of 59 was reached. Again height readings were taken at three positions. Immediately following 60 revolutions, the specimen was leveled using the GTM leveling mechanism and the height reading was taken.

The compacted specimen (contained in the mold) was then removed from the GTM and allowed to cool in air until no deformation would result when removing it from the mold. The cooled specimen was extruded, allowed to cool further to room temperature, and then weighed for unit weight calculations.

Two specimens were prepared for each asphalt content of 5.0, 5.5, 6.0, 6.5 and 7.0 percent (by weight of aggregate) for limestone mixtures and 4.5, 5.0, 5.5, 6.0 and 6.5 percent (by weight of aggregate) for gravel mixtures. Aggregate gradation B was used for the design. The order of preparation of specimens was randomized using random tables (12).

Mixture Design Results

Using the sample height, sample weight, percent asphalt, initial gyratory angle and gyrograph band widths, calculations were made for the following properties (11):

1) Unit weight total mix
2) Unit weight aggregate only

3) Gyratory elasto-plastic index (GEPI)

$$\text{GEPI} = \frac{\text{Minimum Intermediate gyrograph band width}}{\text{Initial gyratory angle}}$$

4) Gyratory stability index (GSI)

$$\text{GSI} = \frac{\text{Maximum gyrograph band width}}{\text{Minimum intermediate gyrograph band width}}$$

5) Gyratory compactibility index (GCI)

$$\text{GCI} = \frac{\text{Unit weight at 30 revolutions}}{\text{Unit weight at 60 revolutions}}$$

The gyrograph band width was obtained by counting vertically the total number of small divisions over which the gyrograph extended (Figure 6). The initial gyratory angle value was substituted in the form of a number of small divisions on the chart (for the GTM used in this investigation, eight small divisions equaled 1 degree).

The calculated mixture property values are presented in Tables 8 and 9. These values are graphically represented in Figures 7 to 10.

The main criteria for mixture design (11) were the gyratory stability index, the unit weight (aggregate only) and the gyratory elasto-plastic index values. The other two properties were utilized only for reference and are not mentioned in the following analysis.

The limestone mixture, as shown by the stability index plot of Figure 8, started losing its stability at 5.5 percent asphalt. This indicates that the design asphalt content from

Table 8. Mixture Design Compaction and Shear Strain Properties of Limestone Mixtures

% Asphalt (by wt. of Agg.)	Unit Weight (Total Mix) pcf.		Unit Weight (Aggregate Only) pcf.		Gyratory Elasto-Plastic Index	Gyratory Stability Index	Gyratory Compactibility Index
	30 Rev	60 Rev	30 Rev	60 Rev			
5.0	135.8	139.8	129.3	133.1	1.35	1.00	0.971
5.5	137.0	140.7	129.9	133.3	1.39	1.00	0.973
6.0	137.9	142.1	130.2	134.3	1.40	1.03	0.970
6.5	139.2	143.1	130.7	134.4	1.40	1.06	0.972
7.0	137.8	141.7	128.8	132.5	1.42	1.18	0.972

Table 9. Mixture Design Compaction and Shear Strain Properties of Gravel Mixtures

% Asphalt (by wt. of Agg.)	Unit Weight (Total Mix) pcf.		Unit Weight (Aggregate Only) pcf.		Gyratory Elasto-Plastic Index	Gyratory Stability Index	Gyratory Compactibility Index
	30 Rev	60 Rev	30 Rev	60 Rev			
4.5	145.5	148.0	139.2	141.6	1.46	1.00	0.983
5.0	146.7	149.5	139.7	142.3	1.52	1.02	0.981
5.5	147.6	150.1	140.0	142.4	1.50	1.03	0.984
6.0	147.7	149.9	139.4	141.4	1.52	1.11	0.986
6.5	147.8	149.8	138.8	140.6	1.66	1.46	0.987

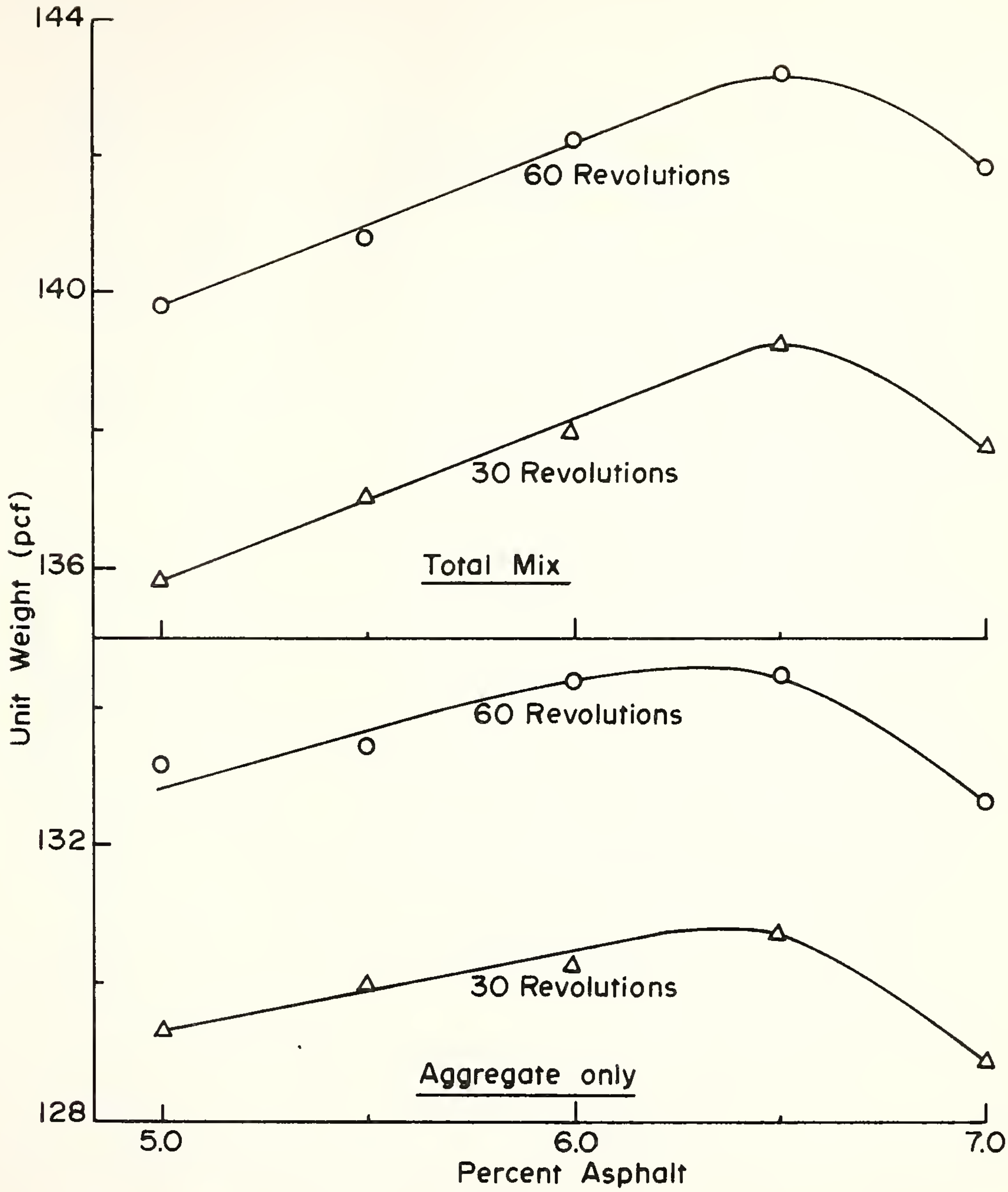


FIGURE 7 - UNIT WEIGHT Vs. PERCENT ASPHALT FOR LIMESTONE MIXTURE DESIGN.

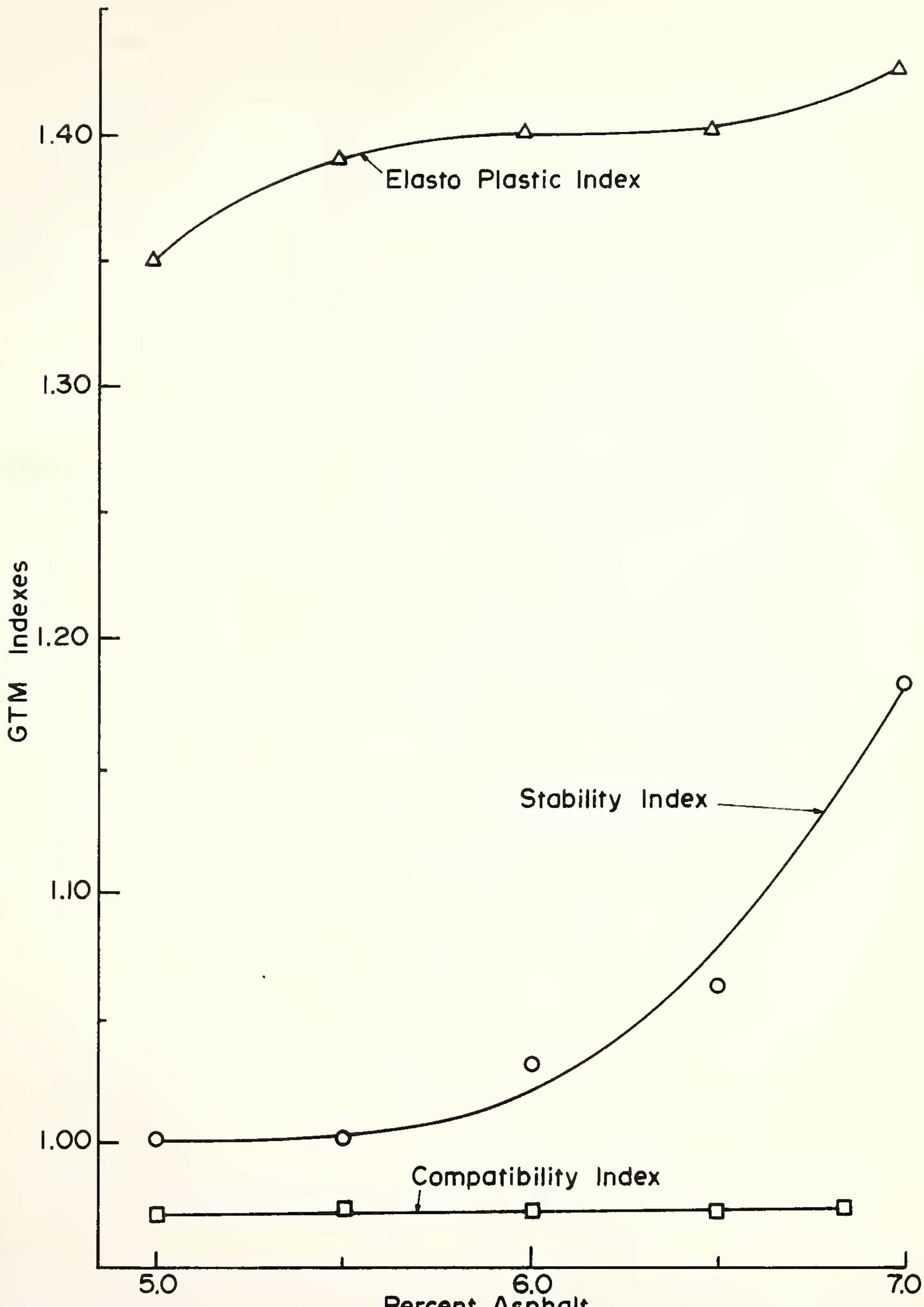


FIGURE 8 - GTM INDEXES Vs. PERCENT ASPHALT FOR LIMESTONE MIXTURE DESIGN.

the stability standpoint should be about 5.5 percent. From the unit weight (aggregate only) point of view, the design value is about 6.5 percent (Figure 7). Taking an average value of the two, 6.0 percent was selected as the design asphalt content for the limestone mixture. From the elasto-plastic index plot (Figure 8), the design asphalt content should not exceed about 6.5 percent.

The gravel mixture started losing its stability at about 4.5 percent asphalt (Figure 10). As is evident from Figure 9, 5.5 percent asphalt gave the maximum value of unit weight (aggregate only). Consequently, the design asphalt content of 5.0 percent was selected for the gravel mixture design. This satisfied the elasto-plastic index requirement of a maximum of 6.0 percent asphalt for the design (Figure 10).

Therefore, for gradation B, the design asphalt contents for limestone and gravel mixtures were selected to be 6.0 percent and 5.0 percent respectively.

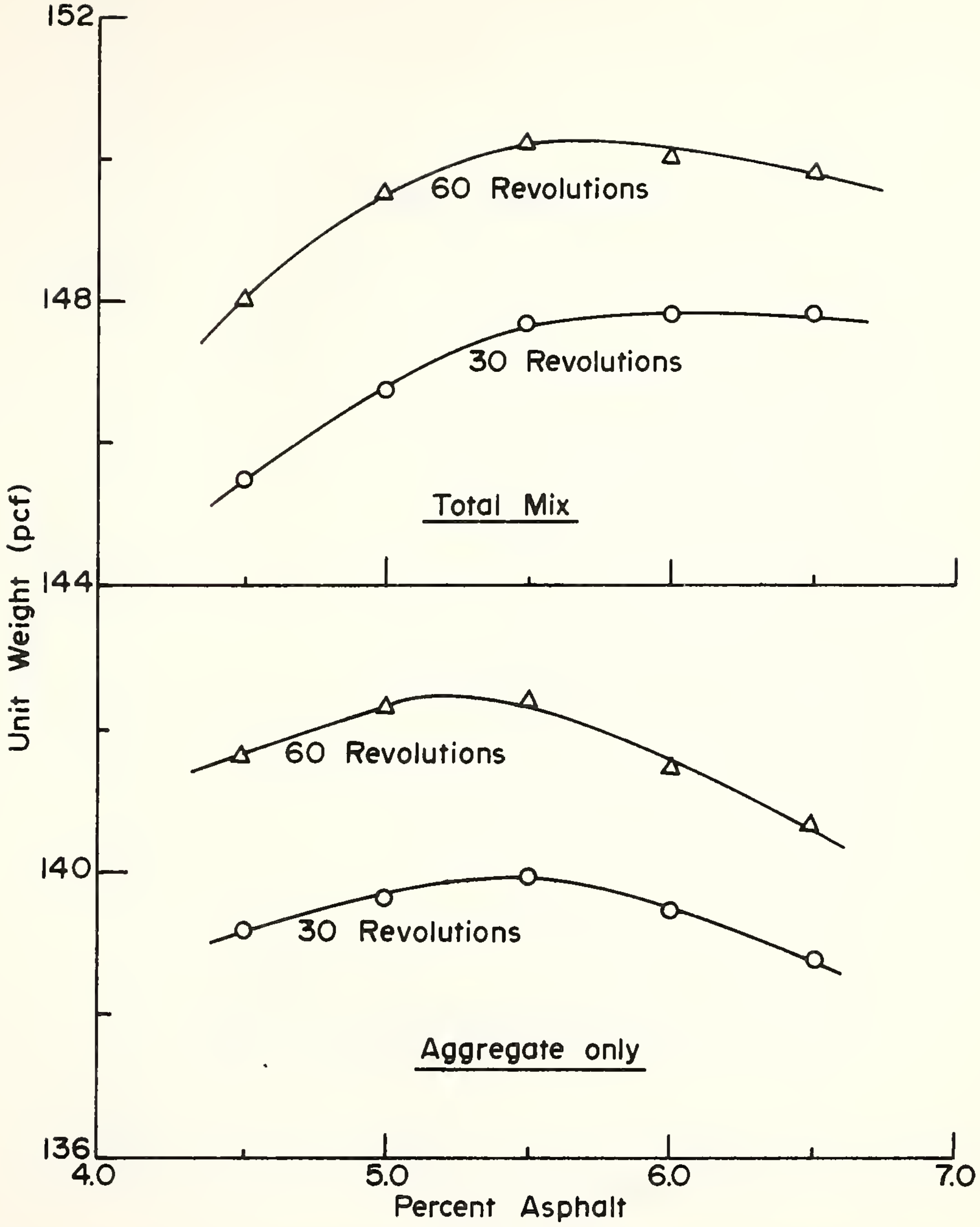


FIGURE 9 - UNIT WEIGHT Vs. PERCENT ASPHALT FOR GRAVEL MIXTURE DESIGN.

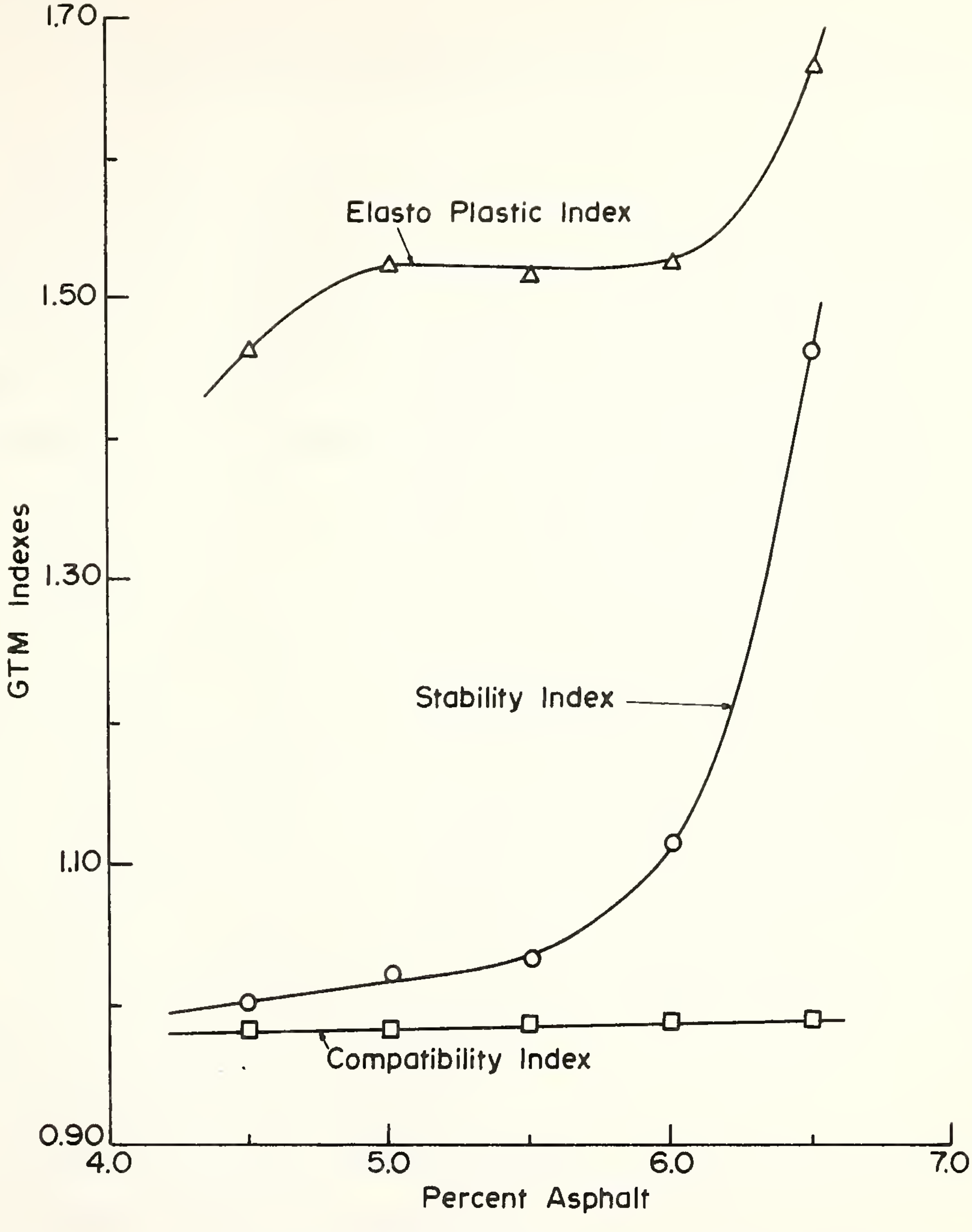


FIGURE 10 - GTM INDEXES Vs. PERCENT ASPHALT FOR GRAVEL MIXTURE DESIGN.

EVALUATION PROCEDURE AND TEST RESULTS

The limestone and gravel mixes of gradation B and design asphalt content were now subjected to the job mix formula tolerances. Each specimen prepared from a different batch was compacted using the GTM simulated field compaction technique followed by GTM simulated traffic densification testing. Mixture properties were calculated based on the observations made. This was done with a view to study the mixture behavior in terms of its properties under simulated traffic conditions and to examine if the difference in mixture property values resulting from variations in the designed gradation and percent asphalt as established by the tolerance limits of the job mix formula were significant. The data were also utilized in evaluating the design procedure.

The entire procedure of compaction and testing is presented in the following sequence.

Simulated field compaction

Simulated traffic densification

Mixture property calculations

Simulated Field Compaction

For limestone mixtures, duplicate specimens were prepared with asphalt contents of 5.7, 6.0 and 6.3 percent for each of the three gradations A, B and C (Figure 3). All eighteen specimens were prepared in a random order (12). For gravel mixes, asphalt contents of 4.7, 5.0, and 5.3 percent were used for each gradation A, B, and C. The order of preparation for these eighteen specimens was also randomized (12).

The above mixes were prepared using the same procedure described earlier under the heading 'Mixture Preparation'. Specimen compaction was achieved by using a GTM procedure which provides for simulated steel wheel roller compaction. The method is briefly described as follows (7): The upper roller of the gyratory testing machine was changed from a fixed to an air roller. The GTM was set for a 3 degree angle of gyration, 100 psi ram pressure and a 15.0 psi air roller pressure. The chuck heater, adjusted to 140^{o}F, was switched on one hour before the compaction of the first specimen.

The heated mold (250^{o}F), base plate and paper disc were placed on the carrying tray. Using a wide mouth funnel the contents of the mixing bowl were transferred into the mold. Another paper disc was placed on top of the mixture and the mixture was compressed by hand with a 4-inch diameter plunger until it was 3/8" to 1/2" below the top of the mold. The mixture was then ready for compaction (Figure 11). The mold containing the mix was placed in the GTM and the vertical pressure was applied. Immediately after clamping the mold, the roller carriage was actuated and the specimen was

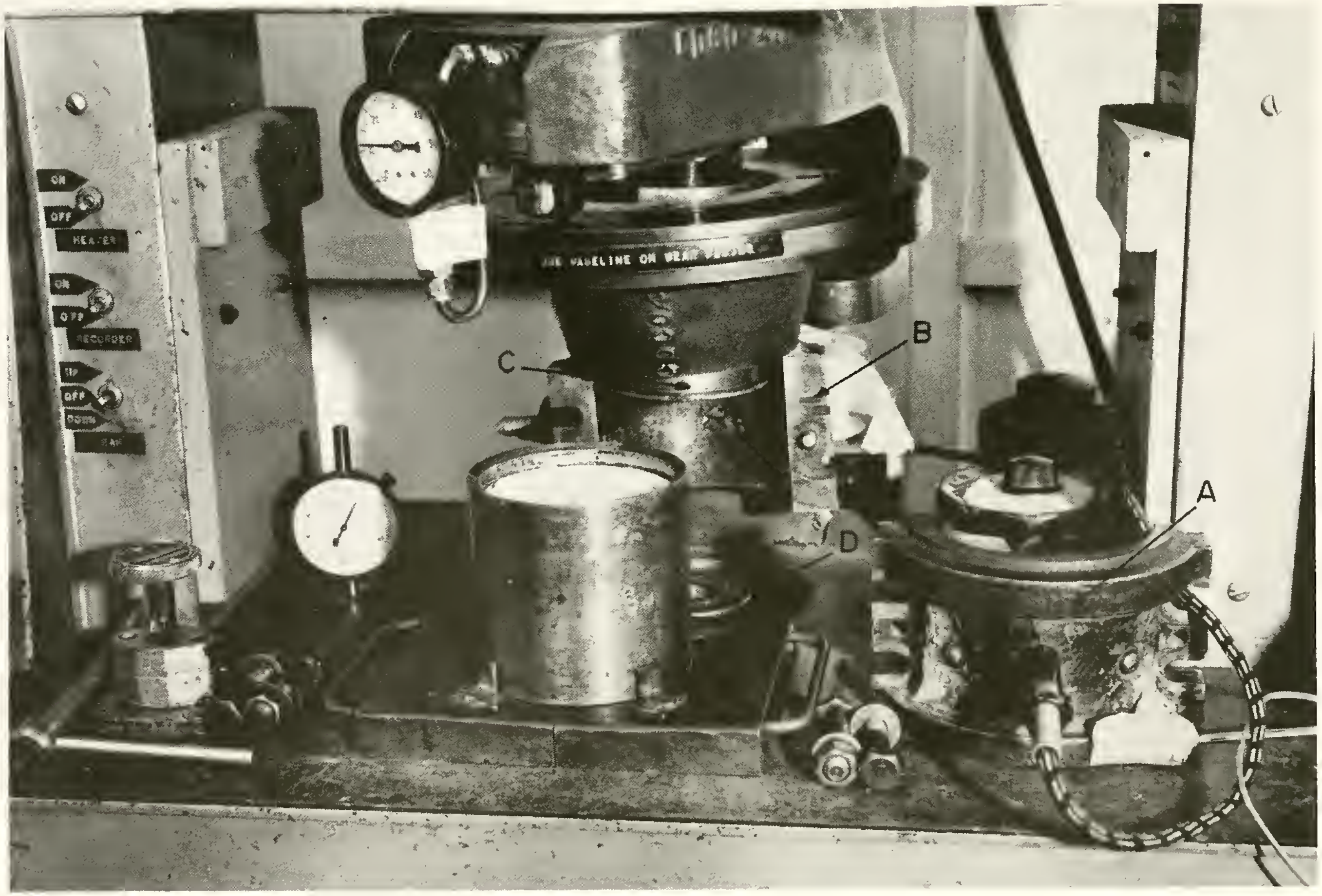


FIGURE 11 - SPECIMEN READY FOR COMPACTION.

Key to details of Figure 11

A. Front mold chuck

B. Back mold chuck

C. Upper ram shaft

D. Lower ram shaft

subjected to 12 revolutions. The mold containing the compacted specimen was then removed from the GTM and placed on its side and allowed to cool. The cooled specimen (contained in the mold) was then placed in an oven at 140^{O}F over night.

Simulated Traffic Densification

Next, the compacted specimen was subjected to simulated traffic densification using the GTM. Following is a brief description of the procedure used (8):

The GTM settings were readjusted to a 2 degree angle of gyration, 2C psi air roller pressure, and 100 psi ram pressure.

The temperature of the mold chuck was controlled to 150 $\pm$ 1^{O}F with the help of a Dyna-Sense Electronic Temperature Controller. Since the back chuck heater has more metal to heat and more surface area to radiate heat, excess heat was supplied to it and the settings adjusted so that both front and back mold chuck had the same temperature at the inner surface in contact with the mold. The chuck heater was switched on two hours before starting the testing. Simultaneously, a dummy specimen contained in the mold was placed in the oven for one hour at 180^{O}F. The mold containing the specimen was then removed from the oven and clamped in the GTM for one hour. This helped in heating the upper and lower ram shafts and thus in stabilizing the temperature of the specimen. In order to establish the heater settings, temperatures were measured at the center of the specimen, at the circumfrential surface of the specimen in contact with the mold, and of the mold chuck at regular intervals of time (Figure 12). It was observed that the temperature stabilized at 131^{o}F and 142^{o}F in the center and at the surface, respectively, when the temperature of the mold was set to 150^{o}F. Thus, this temperature setting of the mold chucks kept the specimen temperature close to the densification testing temperature of 140^{o}F.

The dummy specimen was removed after one hour and the machine was then ready for densification testing. The mold containing the compacted specimen, kept in the oven at 140^{o}F for over night, was removed and placed in the GTM. After applying the vertical pressure, the mold was clamped in the GTM mold chuck. The initial specimen height was recorded and the gyrograph recorder switch was turned on. The roller carriage was then actuated. The testing was stopped at 50, 100, 200, 300, 500, 750 and 1000 revolutions to record the sample height and air roller pressure readings. At the end of 1000 revolutions, the mold was removed from the GTM and the specimen was extruded. The specimen was weighed after it had cooled to room temperature.

Mixture Property Calculations

Using specimen height, specimen weight, percent asphalt, air roller pressure and gyrograph band widths, calculations were made to obtain the following properties for each of the

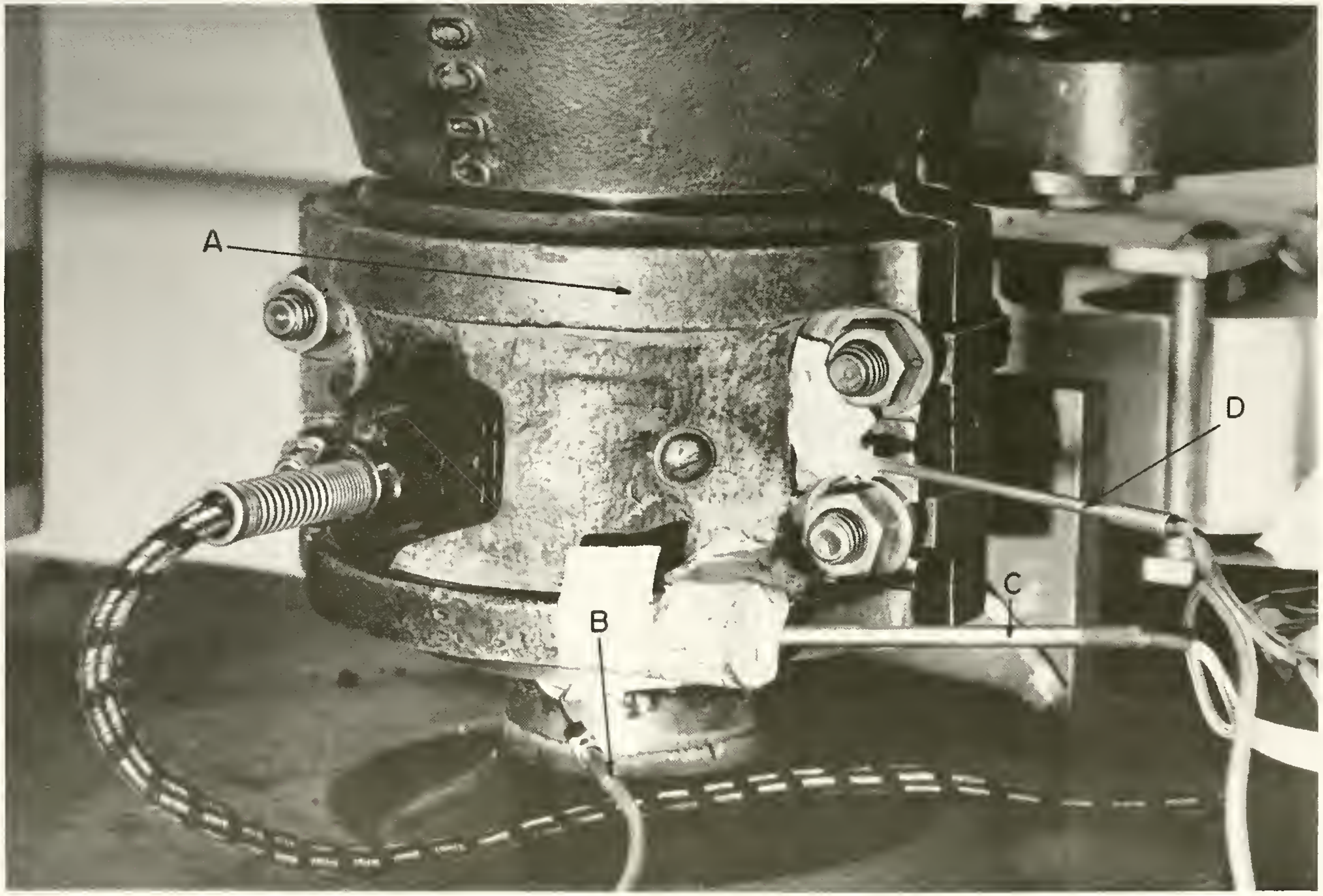


FIGURE 12 - TEMPERATURE MEASUREMENT OF THE SPECIMEN.

Key to details of Figure 12

A. Front mold chuck

B. Measures temperature at the circumfrential surface of the specimen

C. Measures temperature of the front mold chuck

D. Measures temperature at the center of the specimen thirty-six specimens representing the eighteen mixtures:

1) Unit weight total mix

2) Unit weight aggregate only

3) Gyratory shear value (G_s)

$$G_s = \frac{2.1p}{h}$$

Where G_s = Gyratory shear value

p = Air roller pressure in psi

h = Height of the specimen in inches

4) Gyratory stability index (GSI_{50}^{x})

$$GSI_{50}^{x} = \frac{\text{Gyrograph width at x revolutions of densification}}{\text{Gyrograph width at 50 revolutions of densification}}$$

5) Gyratory compactibility index (GCI_{50}^{x})

$$GCI_{50}^{x} = \frac{\text{Unit weight of total mix at x revolutions of densification}}{\text{Unit weight of total mix at 50 revolutions of densification}}$$

The calculated values for the duplicate specimens and their averages are presented in Appendix B (Tables 16 to 25). Figures 13 to 22 show these average mixture property values plotted against number of revolutions. Mixture property values versus percent asphalt content plots at 500 and 1000 revolutions for both limestone and gravel mixes are shown in Figures 23 to 27 and 30 to 34, respectively. Since the analyses made on the basis of these plots alone can be misleading, the entire mixture property data were also analyzed statistically (13). Summaries of the statistical results are presented in Tables 10 to 15 and Figures 28, 29, 35 and 36. Details of the analyses are presented in Appendix C, Tables 26 to 44.

ANALYSIS OF TEST RESULTS

The calculated mixture properties were utilized to study the following factors in order:

Influence of simulated traffic densification on the mixture properties

Job mix formula and the tolerance limits

Evaluation of the GTM design method

Influence of Simulated Traffic Densification on the Mixture Properties

This section deals with the evaluation of compaction and shear strain properties of the mixtures composed of all possible combinations of gradation A, B and C with three different percentages of asphalt content (5.7, 6.0 and 6.3 percent for limestone and 4.7, 5.0 and 5.3 percent for gravel mixtures).

Figures 13 through 22 illustrate the variations in mixture properties with increasing simulated traffic densification. Analysis of variance tests were conducted on the mixture property values to statistically analyze the overall effect of gradation, percent asphalt and number of revolutions. The results are summarized in Tables 10 and 11 and in Tables 12 and 13 for limestone and gravel mixes, respectively. These tables also present the effects due to interaction between the three factors, gradation, percent asphalt and number of revolutions. These interaction results are not utilized in this analysis since they were not of much importance to the present study.

Examining the limestone mixtures first, the unit weight (total mix) plot (Figure 13) shows a general gain in unit weight with increasing number of revolutions. The curves have more slope initially, then tend to flatten as the number of revolutions increases. This trend is more predominant in gradations B and C than in gradation A. Use of different percentages of asphalt content tends to shift the entire curve but does not change its general shape. Analysis of variance test results (Table 10 and 11), up to both 500 and 1000 revolutions, show that all of the three variables, gradation, percent asphalt and number of revolutions, significantly (at the 5 percent level) affected the property values.

The plot of unit weight (aggregate only) shows (Figure 14) the same tendency as that of unit weight (total mix) curves. Analysis of variance test results were also the same except that the influence of percent asphalt content did not show any significance when tested up to 500 revolutions. This indicates that the role of quantity of asphalt is not so significant in the earlier stages of traffic densification.

The gyratory shear plot (Figure 15) indicates an increase in shear value with increasing number of revolutions for all specimens except B6.3, C6.0 and C6.3 (the letter

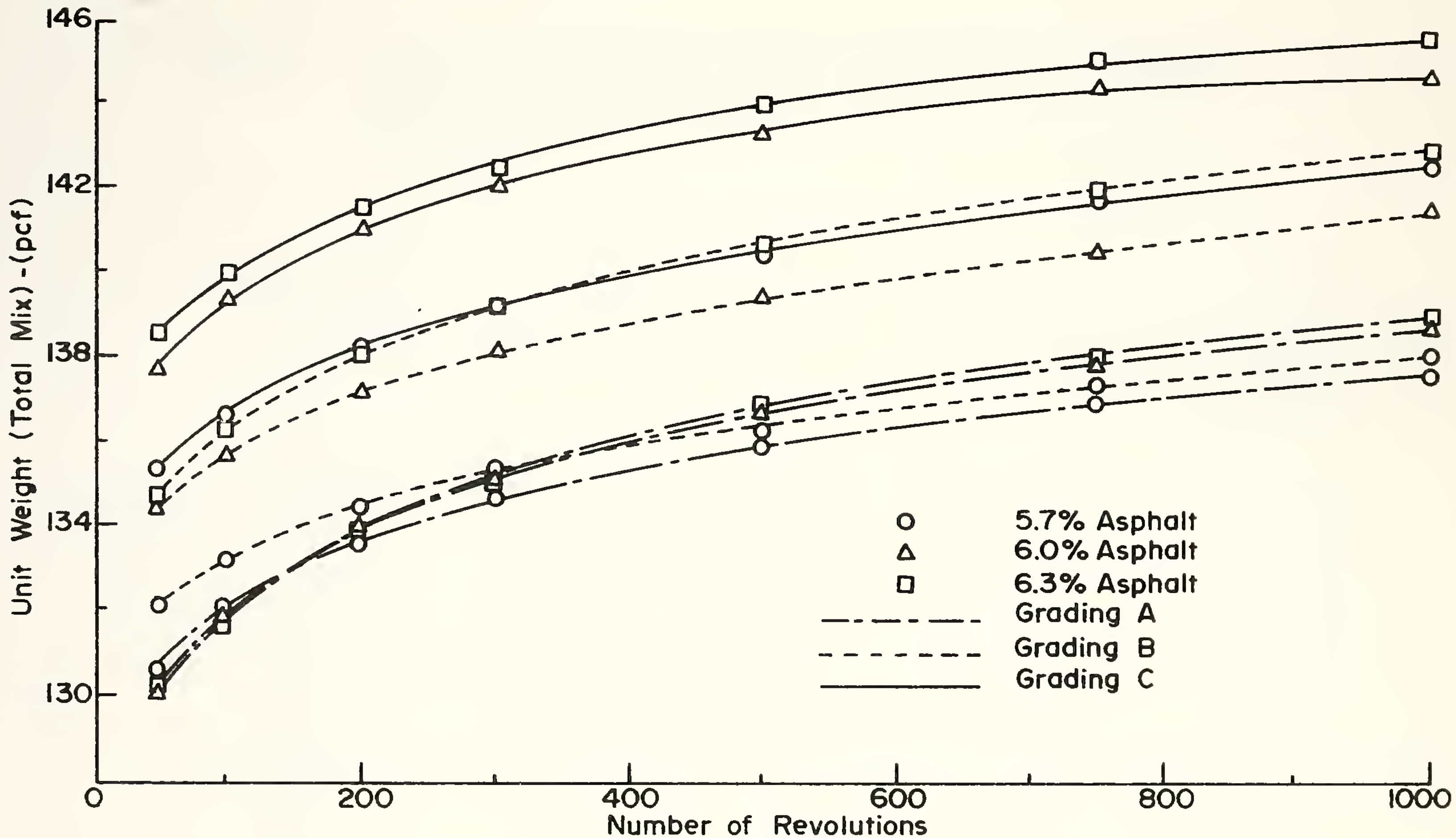


FIGURE 13 - INFLUENCE OF SIMULATED TRAFFIC DENSIFICATION ON LIMESTONE MIXTURE PROPERTIES - UNIT WEIGHT (TOTAL MIX).

Table 10. Influence of Gradation, % Asphalt and Revolution on Limestone Mixture Properties upto 500 Revolutions (Results of Analysis of Variance Test)

H_o: Mixture Properties not affected by factor (α = 0.05)

Factor	Unit Weight (Total Mix)	Unit Weight (Aggregate Only)	Gyratory Shear	Gyratory Stability Index (GSI^x_{50})	Gyratory Compactibility Index (GCI^x_{50})
I - GRADATION	Reject H_o	Reject H_o	Accept H_o	Reject H_o	Reject H_o
J - ASPHALT	Reject H_o	Accept H_o	Accept H_o	Reject H_o	Reject H_o
L - REVOLUTION	Reject H_o	Reject H_o	Reject H_o	Reject H_o	Reject H_o
IJ	Accept H_o	Accept H_o	Accept H_o	Accept H_o	Accept H_o
IL	Reject H_o	Reject H_o	Accept H_o	Reject H_o	Reject H_o
JL	Reject H_o	Reject H_o	Accept H_o	Reject H_o	Reject H_o
IJL	Reject H_o	Reject H_o	Reject H_o	Accept H_o	Reject H_o

Table 11. Influence of Gradation, % Asphalt and Revolution on Limestone Mixture Properties upto 1000 Revolutions (Results of Analysis of Variance Test)

H_o: Mixture Properties not affected by factor ($\alpha = 0.05$)

Factor	Unit Weight (Total Mix)	Unit Weight (Aggregate Only)	Gyratory Shear	Gyratory Stability Index (GSI^x_{50})	Gyratory Compactibility Index (GCI^x_{50})
I - GRADATION	Reject H_o	Reject H_o	Accept H_o	Reject H_o	Reject H_o
J - ASPHALT	Reject H_o	Reject H_o	Accept H_o	Reject H_o	Reject H_o
L - REVOLUTION	Reject H_o	Reject H_o	Reject H_o	Reject H_o	Reject H_o
IJ	Accept H_o	Accept H_o	Accept H_o	Accept H_o	Accept H_o
IL	Reject H_o	Reject H_o	Reject H_o	Reject H_o	Reject H_o
JL	Reject H_o	Reject H_o	Reject H_o	Reject H_o	Reject H_o
IJL	Reject H_o	Reject H_o	Reject H_o	Reject H_o	Reject H_o

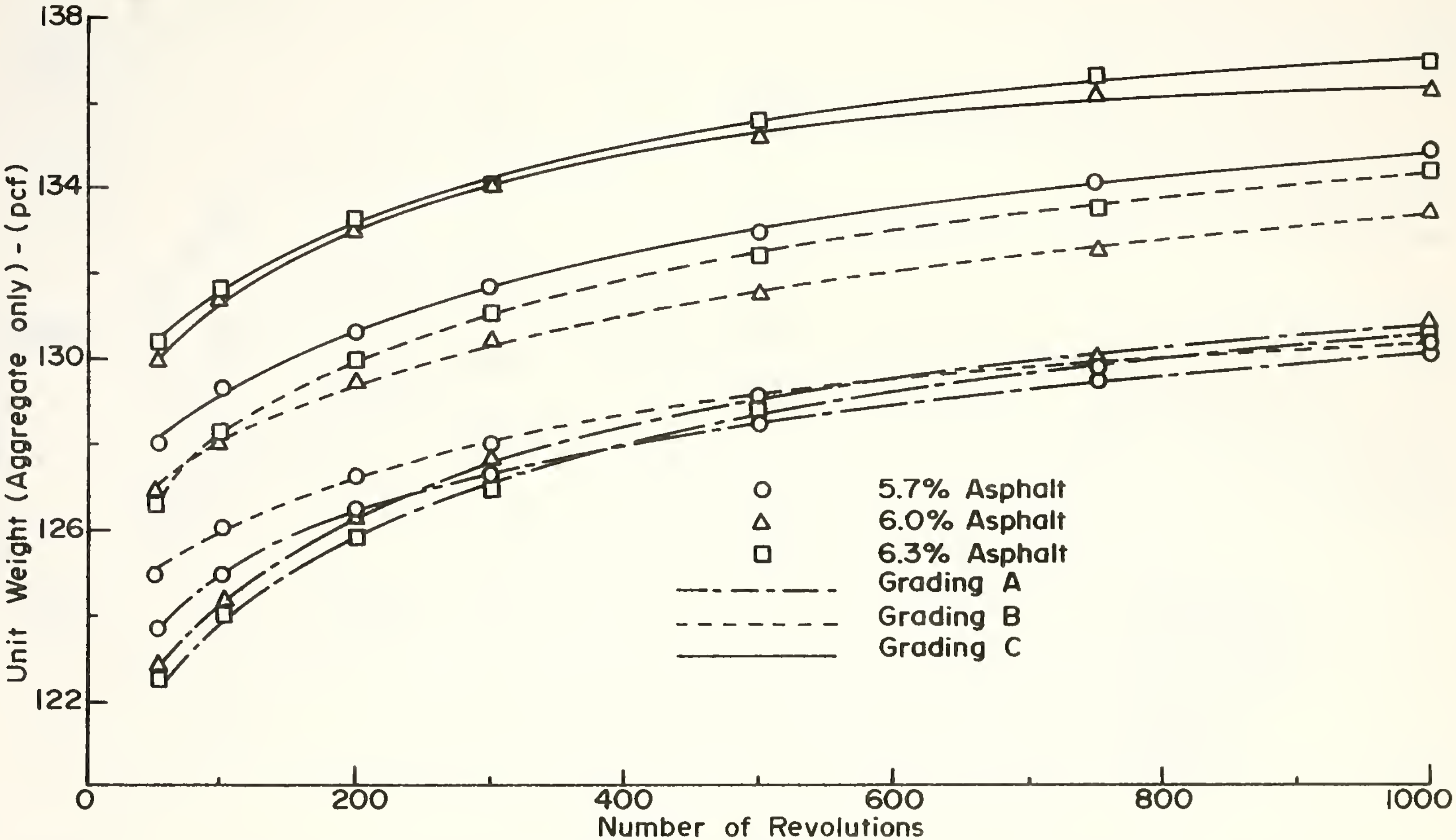


FIGURE 14 - INFLUENCE OF SIMULATED TRAFFIC DENSIFICATION ON LIMESTONE MIXTURE PROPERTIES - UNIT WEIGHT (AGGREGATE ONLY).

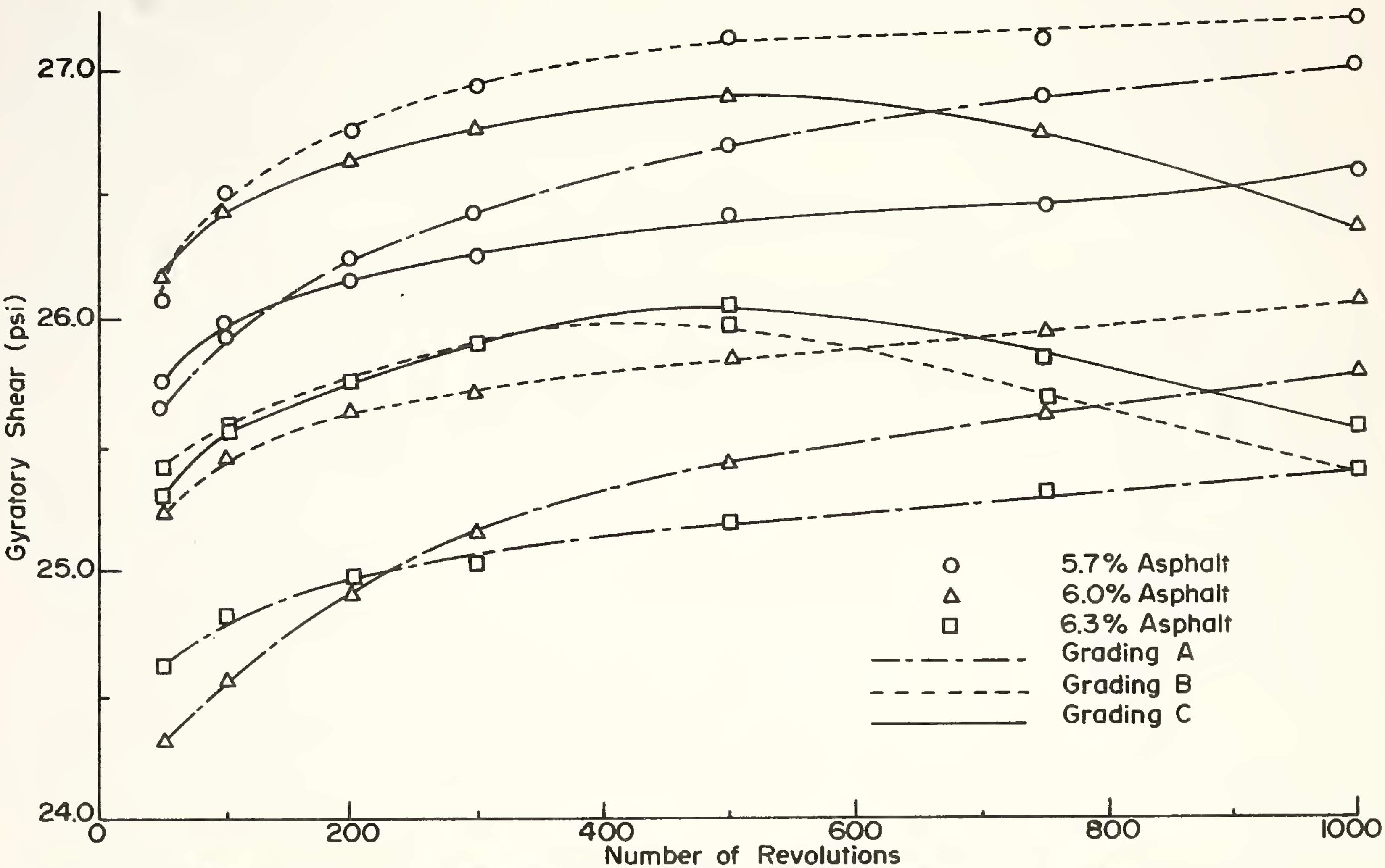


FIGURE 15- INFLUENCE OF SIMULATED TRAFFIC DENSIFICATION ON LIMESTONE MIXTURE PROPERTIES - GYRATORY SHEAR .

designates gradation and the figure represents percent asphalt content). The shear values for these specimens increased up to 500 revolutions, then started to decrease rapidly with increasing number of revolutions. Analysis of variance test results indicate (Tables 10 and 11) that only number of revolutions significantly affect the gyratory shear value.

Analyzing the gyratory stability index plot (Figure 16), the stability index value increased (i.e., the mixture starts losing its stability) with increasing number of revolutions. The loss in stability becomes more and more predominant with increase in asphalt content and gradation towards the finer side. According to analysis of variance test results (Tables 10 and 11), all the three variables, gradation, percent asphalt and number of revolutions, significantly affect the gyratory stability index value.

The gyratory compactibility index plot (Figure 17) shows a rapid decrease in this value (i.e. increase in densification) initially and then a tendency for the curves to flatten with increasing number of revolutions. Neither the variations in gradation nor in asphalt content seem to influence the trend of the curves, but all affect the gyratory compactibility index value significantly as is indicated by analysis of variance test results (Tables 10 and 11).

With respect to the gravel mixtures, the unit weight (total mix) plot (Figure 18) shows a rapid increase in this

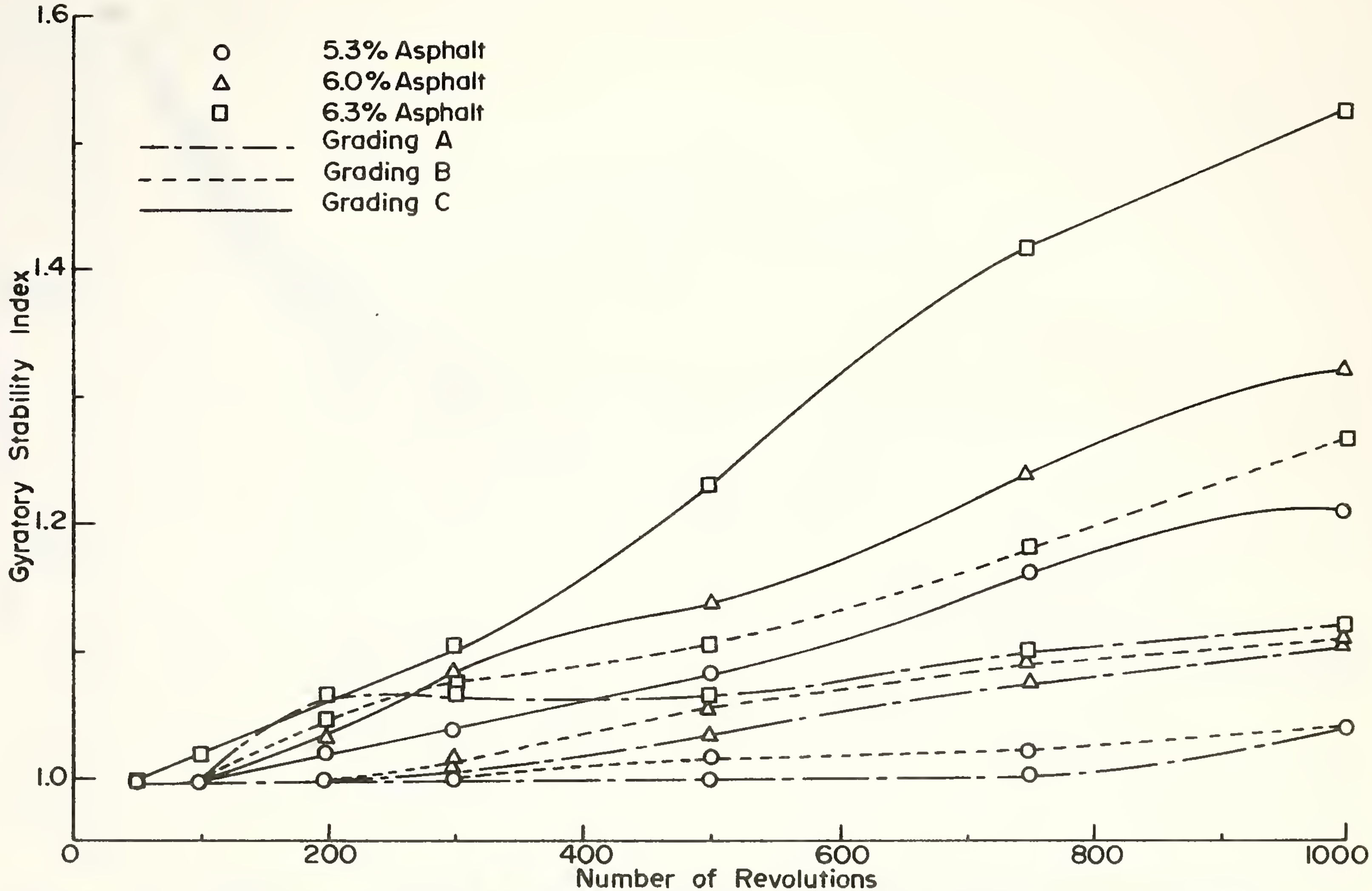


FIGURE 16 - INFLUENCE OF SIMULATED TRAFFIC DENSIFICATION ON LIMESTONE MIXTURE PROPERTIES - GYRATORY STABILITY INDEX (GSI^{x}_{50}).

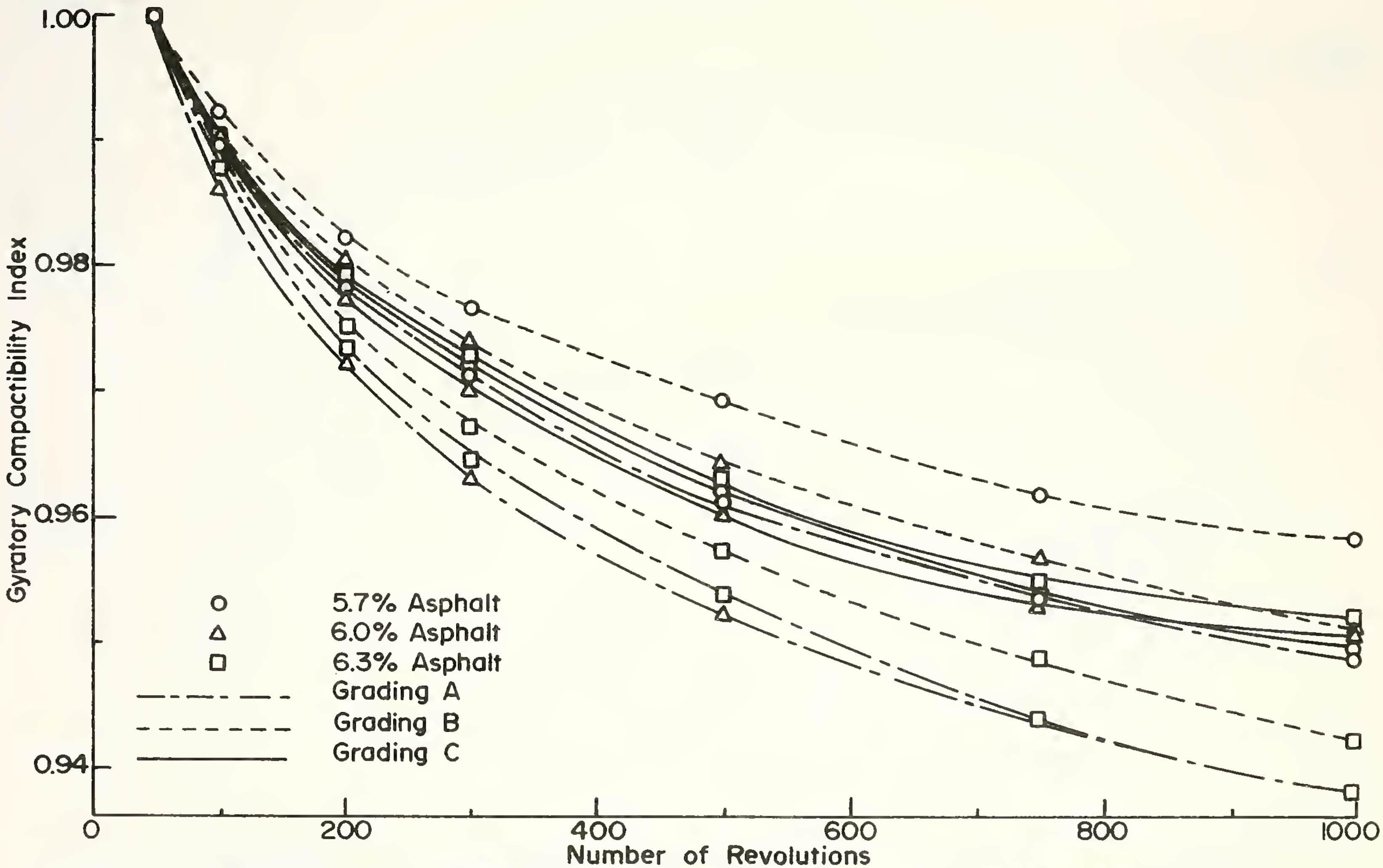


FIGURE 17 - INFLUENCE OF SIMULATED TRAFFIC DENSIFICATION ON LIMESTONE MIXTURE PROPERTIES-GYRATORY COMPACTIBILIT INDEX (GCI^{x}_{50}).

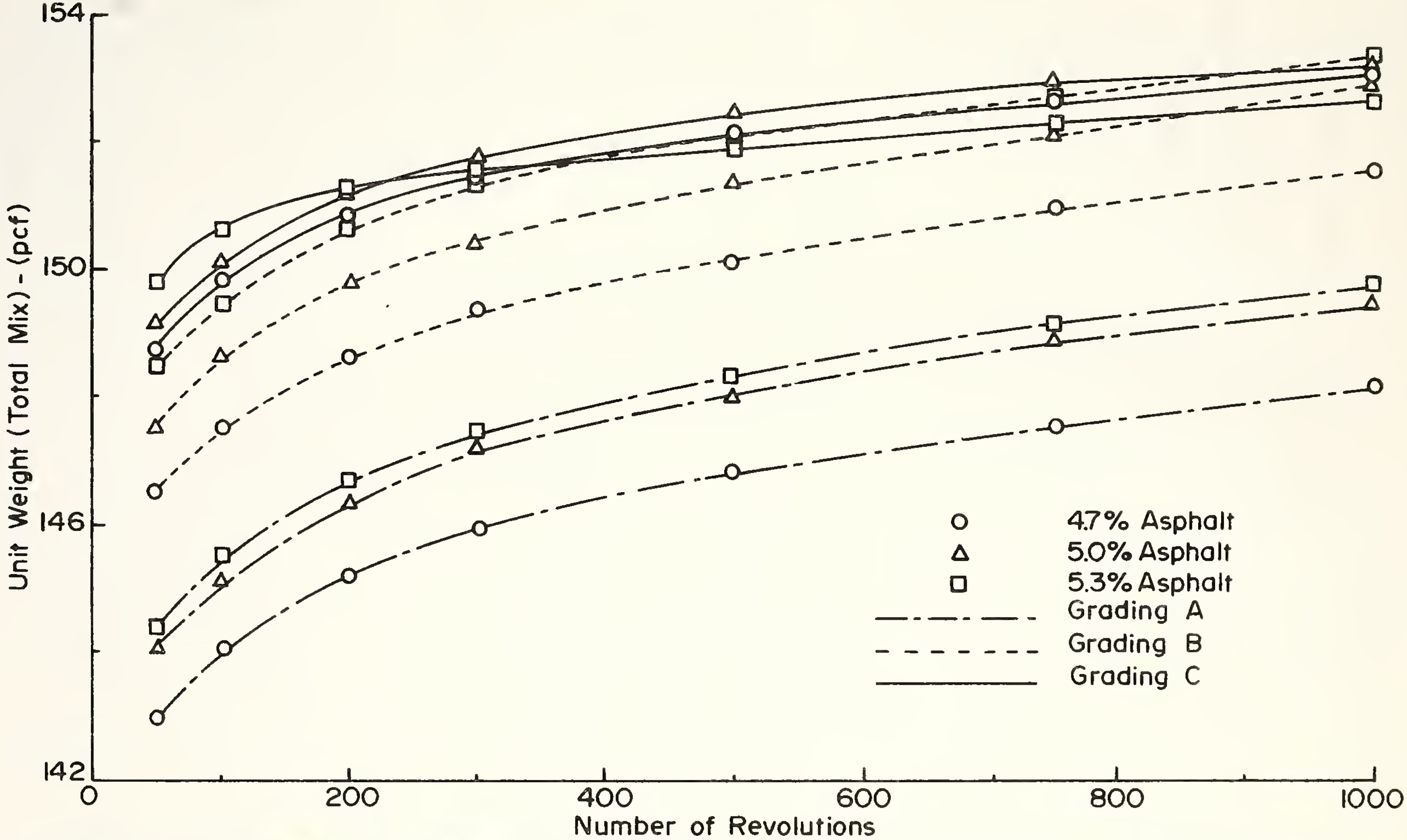


FIGURE 18 - INFLUENCE OF SIMULATED TRAFFIC DENSIFICATION ON GRAVEL MIXTURE PROPERTIES - UNIT WEIGHT (TOTAL MIX).

value initially followed by a flattening of the curve with increasing number of revolutions. Analysis of variance test results show (Tables 12 and 13) that gradation, percent asphalt and number of revolutions significantly affect the unit weight (total mix) values. The unit weight (aggregate only) plot (Figure 19) is similar to the unit weight (total mix) plot. However, only gradation and number of revolutions significantly affect the values both up to 500 and up to 1000 revolutions as is shown by analysis of variance test results (Tables 12 and 13).

The gyratory shear plot (Figure 20) indicates no appreciable increase in shear value with increase in number of revolutions for any mixtures. The gyratory shear value decreases with increasing number of revolutions for specimens having compositions A5.3, B5.3, C4.7, C5.0 and C5.3. Analysis of variance test results (Tables 12 and 13) show that all of the three variables, gradation, percent asphalt and number of revolutions significantly affect the gyratory shear value.

The gyratory stability index value increases (i.e., the mixture loses its stability) with increasing number of revolutions as shown in Figure 21. It was observed that with increasing number of revolutions asphalt started oozing out from the specimen C5.3, thus changing the mixture composition. This resulted in a lower gyratory stability index value as compared to specimen B5.3 for densification beyond 500 revolutions. Analysis of variance test results (Tables

Table 12. Influence of Gradation, % Asphalt and Revolution on Gravel Mixture Properties upto 500 Revolutions (Results of Analysis of Variance Test)

H_o: Mixture Properties not affected by factor ($\alpha = 0.05$)

Factor	Unit Weight (Total Mix)	Unit Weight (Aggregate Only)	Gyratory Shear	Gyratory Stability Index (GSI^x_{50})	Gyratory Compactibility Index (GCI^x_{50})
I - GRADATION	Reject H_o	Reject H_o	Reject H_o	Reject H_o	Reject H_o
J - ASPHALT	Reject H_o	Accept H_o	Reject H_o	Reject H_o	Accept H_o
L - REVOLUTION	Reject H_o	Reject H_o	Reject H_o	Reject H_o	Reject H_o
IJ	Accept H_o	Accept H_o	Reject H_o	Reject H_o	Reject H_o
IL	Reject H_o	Reject H_o	Reject H_o	Reject H_o	Reject H_o
JL	Reject H_o	Reject H_o	Reject H_o	Reject H_o	Reject H_o
IJL	Reject H_o	Reject H_o	Reject H_o	Reject H_o	Reject H_o

Table 13. Influence of Gradation, % Asphalt and Revolution on Gravel Mixture Properties upto 1000 Revolutions (Results of Analysis of Variance Test)

H_o: Mixture Properties not affected by factor ($\alpha = 0.05$)

Factor	Unit Weight (Total Mix)	Unit Weight (Aggregate Only)	Gyratory Shear	Gyratory Stability Index (GSI^x_{50})	Gyratory Compactibility Index (GCI^x_{50})
I - GRADATION	Reject H_o	Reject H_o	Reject H_o	Reject H_o	Reject H_o
J - ASPHALT	Reject H_o	Accept H_o	Reject H_o	Reject H_o	Reject H_o
L - REVOLUTION	Reject H_o	Reject H_o	Reject H_o	Reject H_o	Reject H_o
IJ	Accept H_o	Accept H_o	Reject H_o	Reject H_o	Reject H_o
IL	Reject H_o	Reject H_o	Reject H_o	Reject H_o	Reject H_o
JL	Reject H_o	Reject H_o	Reject H_o	Reject H_o	Reject H_o
IJL	Reject H_o	Reject H_o	Reject H_o	Reject H_o	Reject H_o

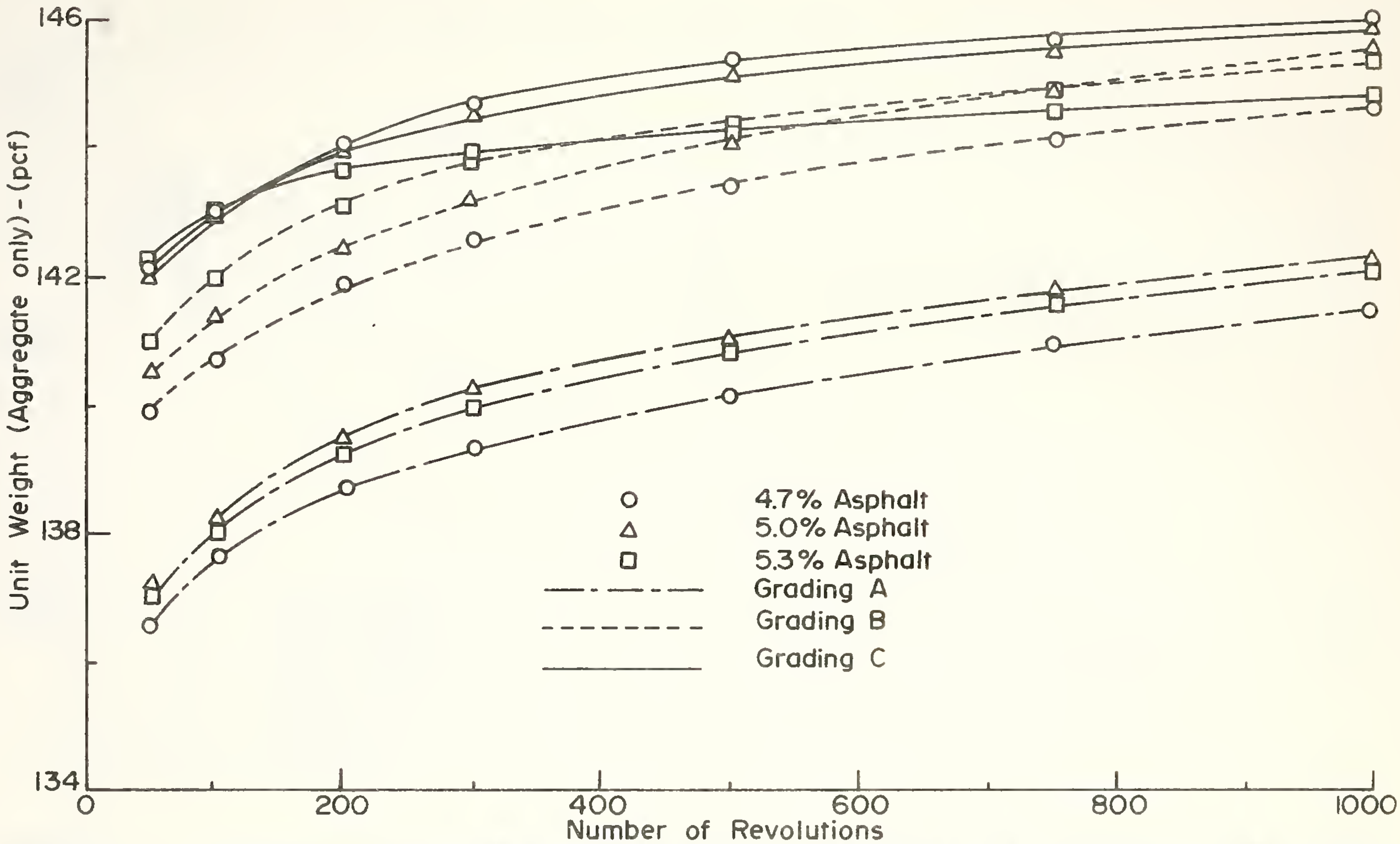


FIGURE 19 - INFLUENCE OF SIMULATED TRAFFIC DENSIFICATION ON GRAVEL MIXTURE PROPERTIES - UNIT WEIGHT (AGGREGATE ONLY).

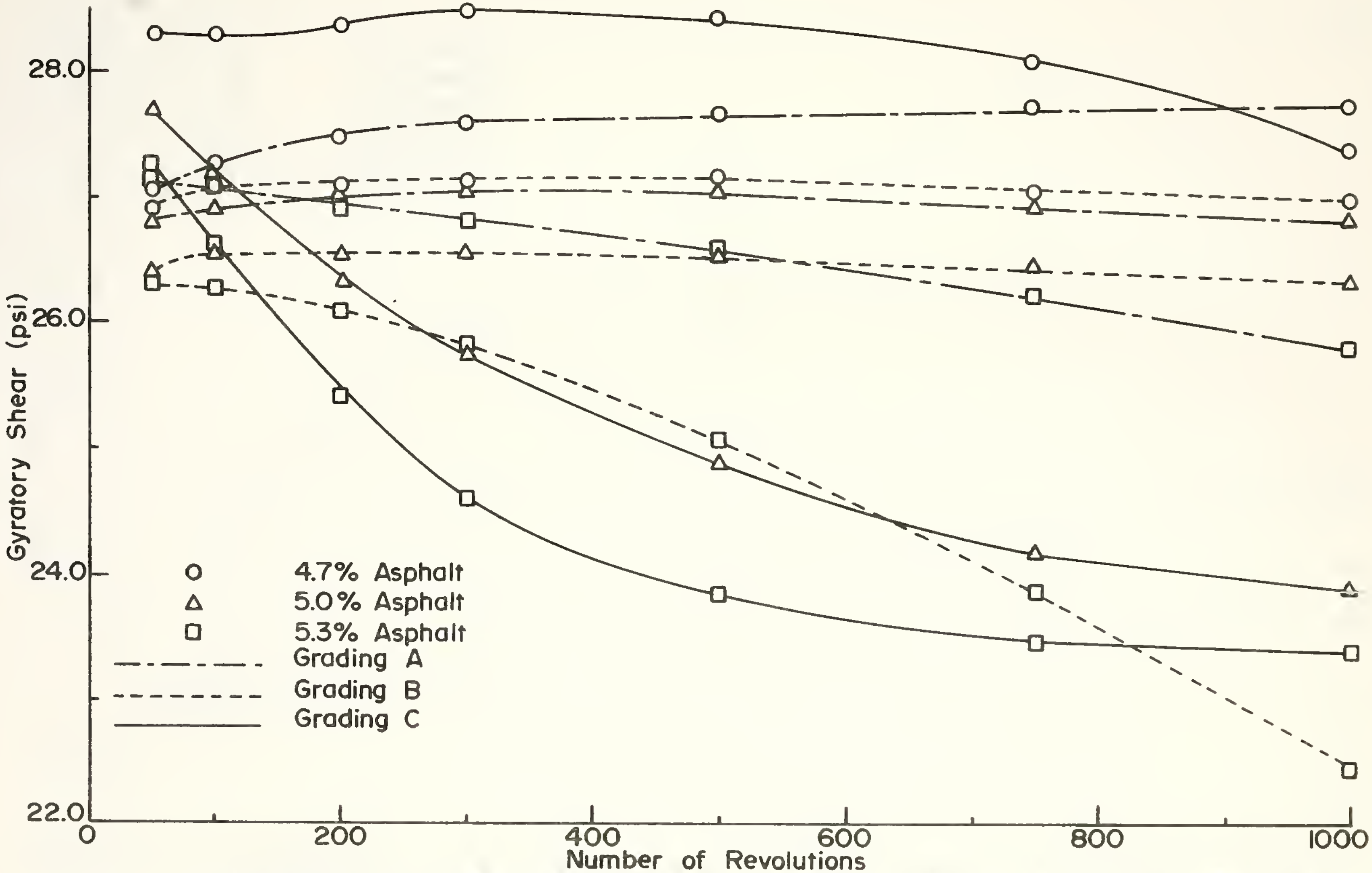


FIGURE 20 - INFLUENCE OF SIMULATED TRAFFIC DENSIFICATION ON GRAVEL MIXTURE PROPERTIES - GYRATORY SHEAR.

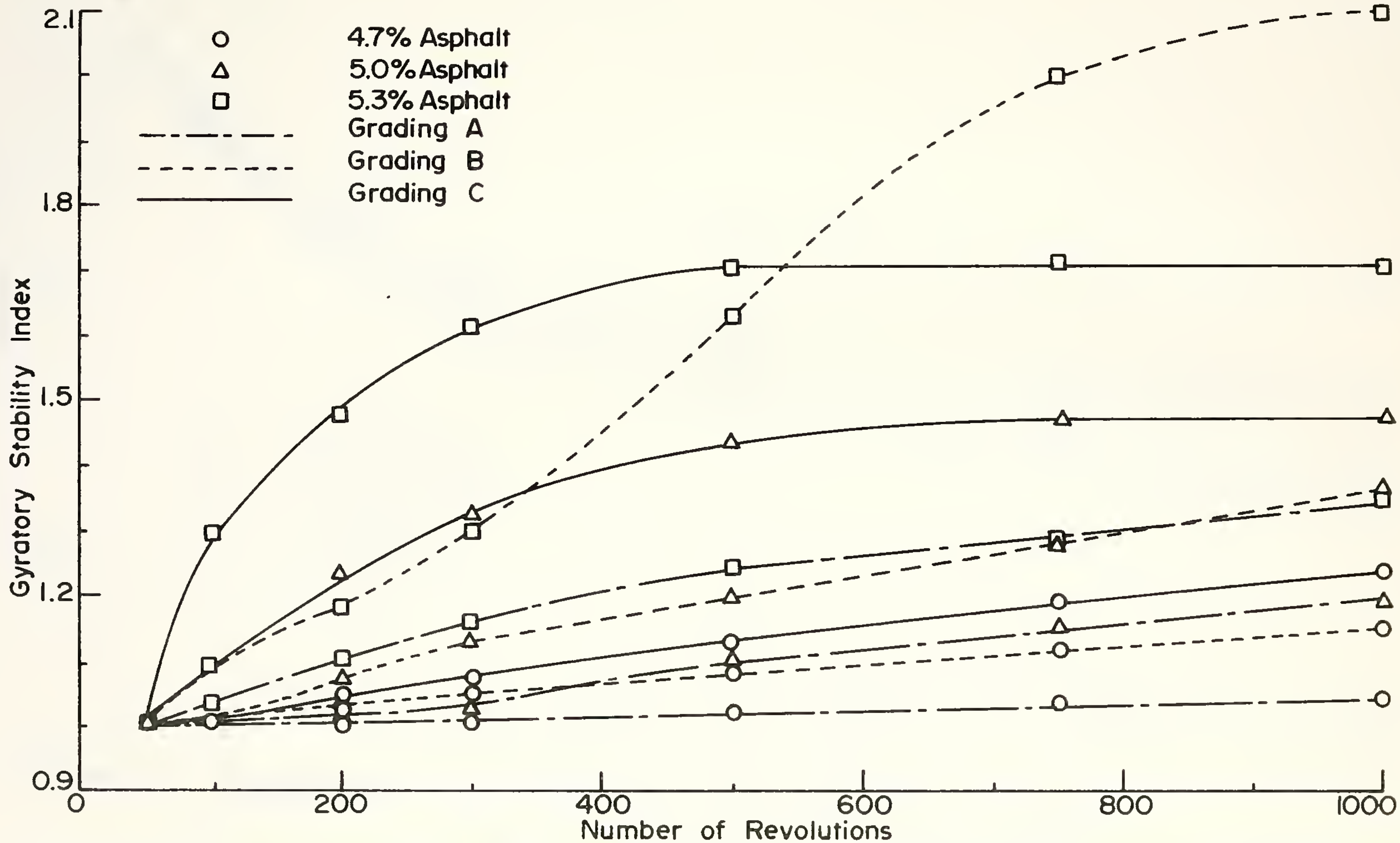


FIGURE 21 - INFLUENCE OF SIMULATED TRAFFIC DENSIFICATION ON GRAVEL MIXTURE PROPERTIES - GYRATORY STABILITY INDEX (GSI^{x}_{50}).

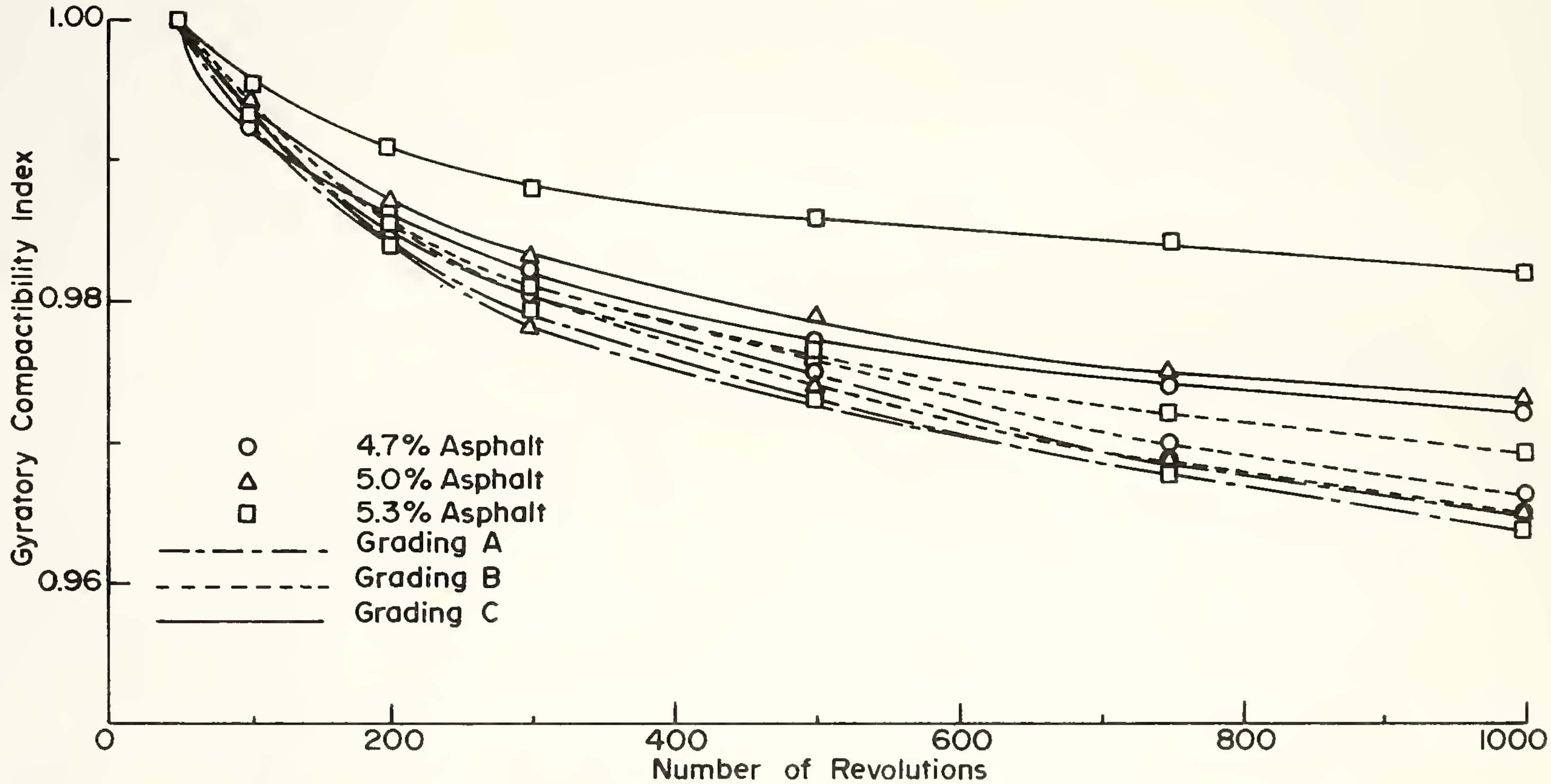


FIGURE 22 - INFLUENCE OF SIMULATED TRAFFIC DENSIFICATION ON GRAVEL MIXTURE PROPERTIES - GYRATORY COMPACTIBILITY INDEX (GCI_{50}^{x}).

12 and 13) show that gradation, percent asphalt and number of revolutions significantly affect the gyratory stability index values.

Analyzing the gyratory compactibility index plot (Figure 22), the gyratory compactibility index value decreases with increasing number of revolutions. The analysis of variance test results (Tables 12 and 13) show that asphalt content is not significant in affecting this mixture property up to 500 revolutions but becomes significant when evaluated up to 1000 revolutions. Gradation and number of revolutions both significantly affect the property value up to 500 and up to 1000 revolutions.

The above discussion indicates that the gyratory testing machine is sensitive enough to predict mixture behavior at any level of traffic densification for both limestone and gravel types of mixes. Therefore, it can be concluded that the use of the gyratory testing machine is both feasible and practical in the evaluation of bituminous mixes.

Job Mix Formula and the Tolerance Limits

In this section an analysis is presented to demonstrate that even if the mixture composition is within the tolerance limits, the mixture property values may be significantly different with respect to the designed mixture property values.

The properties of the specimens with all possible combinations of gradations A, B and C with asphalt contents of 5.7, 6.0 and 6.3 percent for limestone, and 4.7, 5.0 and 5.3 percent for gravel, were considered for this investigation. Two levels of densification, one at 500 gyratory revolutions and the other at 1000 gyratory revolutions were selected for the analysis. Figures 23 through 27 and 30 through 34 present the plots of mixture properties against percent asphalt at 500 and 1000 revolutions for limestone and gravel mixtures, respectively.

Analysis of variance tests were carried out on the mixture property values to determine if there was any significant difference (at the 5 percent level) between the values due to variations in gradation and percent asphalt. The plots were not analyzed if the differences were found to be non-significant. The rest of the plots were studied and another statistical test called the Newman-Keuls Sequential Range Test (NKSRT) was conducted on these mixture property values to test for significance (at the 5 percent level) between each mixture composition.

Analysis of variance test results for limestone mixtures are summarized in Table 14 and those for gravel mixtures in Table 15. These tables also present the effects due to interaction between gradation and percent asphalt. These were not used in this analysis since it was felt they were not helpful in the present study. Figures 28, 29 and 35 and 36 present, in block diagrams, the results of the NKSRT for limestone and gravel mixes respectively (the detailed results are compiled in Appendix C, Tables 26 to 44).

Table 14. Influence of Gradation and Percent Asphalt on Limestone Mixture Properties at 500 and 1000 Revolutions (Results of Analysis of Variance Test)

H_o: Mixture Properties not affected by factor (α = 0.05)

Factor	Unit Weight (Total Mix)	Unit Weight (Aggregate Only)	Gyratory Shear	Gyratory Stability Index (GSI^x_{50})	Gyratory Compactibility Index (GCI^x_{50})
			AT 500 REVOLUTIONS		
I - GRADATION	Reject H_o	Reject H_o	Accept H_o	Reject H_o	Reject H_o
J - ASPHALT	Reject H_o	Reject H_o	Accept H_o	Reject H_o	Reject H_o
IJ	Accept H_o	Accept H_o	Accept H_o	Accept H_o	Accept H_o
			AT 1000 REVOLUTIONS		
I - GRADATION	Reject H_o	Reject H_o	Accept H_o	Reject H_o	Reject H_o
J - ASPHALT	Reject H_o	Reject H_o	Reject H_o	Reject H_o	Reject H_o
IJ	Accept H_o	Accept H_o	Accept H_o	Accept H_o	Accept H_o

Table 15. Influence of Gradation and Percent Asphalt on Gravel Mixture Properties at 500 and 1000 Revolutions (Results of Analysis of Variance Test)

H_o: Mixture Properties not affected by factor ($\alpha = 0.05$)

Factor	Unit Weight (Total Mix)	Unit Weight (Aggregate Only)	Gyratory Shear	Gyratory Stability Index (GSI^x_{50})	Gyratory Compactibility Index (GCI^x_{50})
		AT 500 REVOLUTIONS			
I - GRADATION	Reject H_o	Reject H_o	Reject H_o	Reject H_o	Reject H_o
J - ASPHALT	Reject H_o	Accept H_o	Reject H_o	Reject H_o	Reject H_o
IJ	Accept H_o	Accept H_o	Reject H_o	Reject H_o	Reject H_o
		AT 1000 REVOLUTIONS			
I - GRADATION	Reject H_o	Reject H_o	Reject H_o	Reject H_o	Reject H_o
J - ASPHALT	Accept H_o	Accept H_o	Reject H_o	Reject H_o	Reject H_o
IJ	Accept H_o	Accept H_o	Reject H_o	Reject H_o	Reject H_o

On examining the limestone mixture property values, at 500 revolutions the NKSRT results (at 5 percent level) indicate (Figure 28) that if either gradation A or C was used instead of gradation B, both unit weight (total mix) and unit weight (aggregate only) values were significantly affected. Values were higher for gradation C and lower for gradation A as compared to gradation B (Figures 23 and 24). If 5.7 percent asphalt content was used instead of 6.0 percent, the unit weight (total mix) values were significantly affected and were lower than the designed value (Figures 23 and 28). Use of 6.3 percent asphalt did not significantly affect the designed value. Unit weight (aggregate only) values were not significantly affected if either 5.7 percent or 6.3 percent asphalt was used. The same trend was observed for both unit weight (total mix) and unit weight (aggregate only) at 1000 revolutions (Figures 23, 24 and 29).

The gyratory shear and gyratory compactibility index values (Figures 25 and 27) were not significantly affected (NKSRT results, Figures 28 and 29) at both 500 and 1000 revolutions by variations in gradation and asphalt content. Examining the NKSRT results (Figures 28 and 29) for gyratory stability index values, only gradation C had a significant affect on the values at both 500 and 1000 revolutions resulting in loss in stability (Figure 26). The mixture with 6.3 percent asphalt content resulted in significant loss in stability at 1000 revolutions, whereas at 500 revolutions the loss was

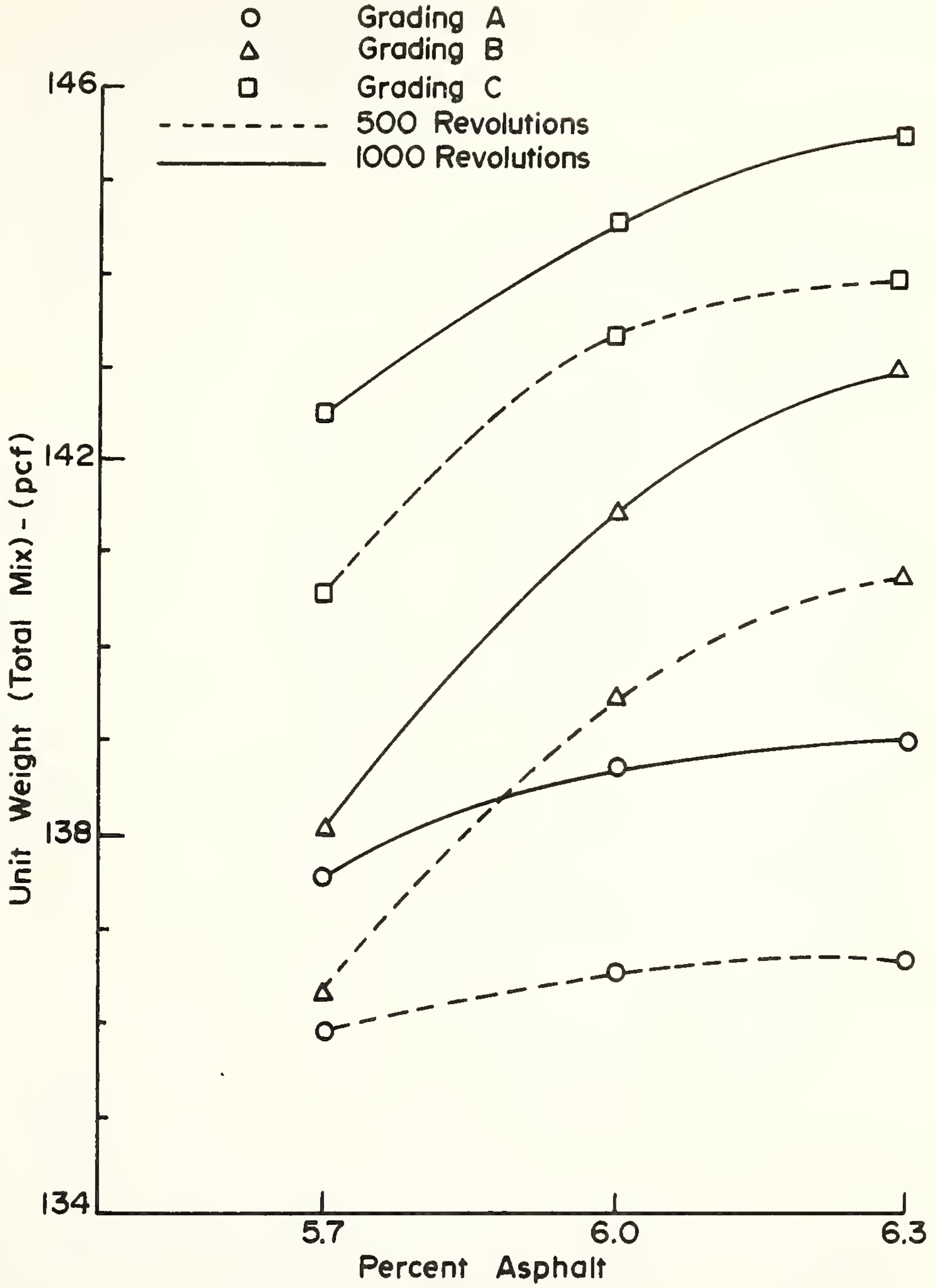


FIGURE 23 - UNIT WEIGHT (TOTAL MIX) Vs. PERCENT ASPHALT FOR LIMESTONE MIXTURES AT TWO LEVELS OF DENSIFICATION.

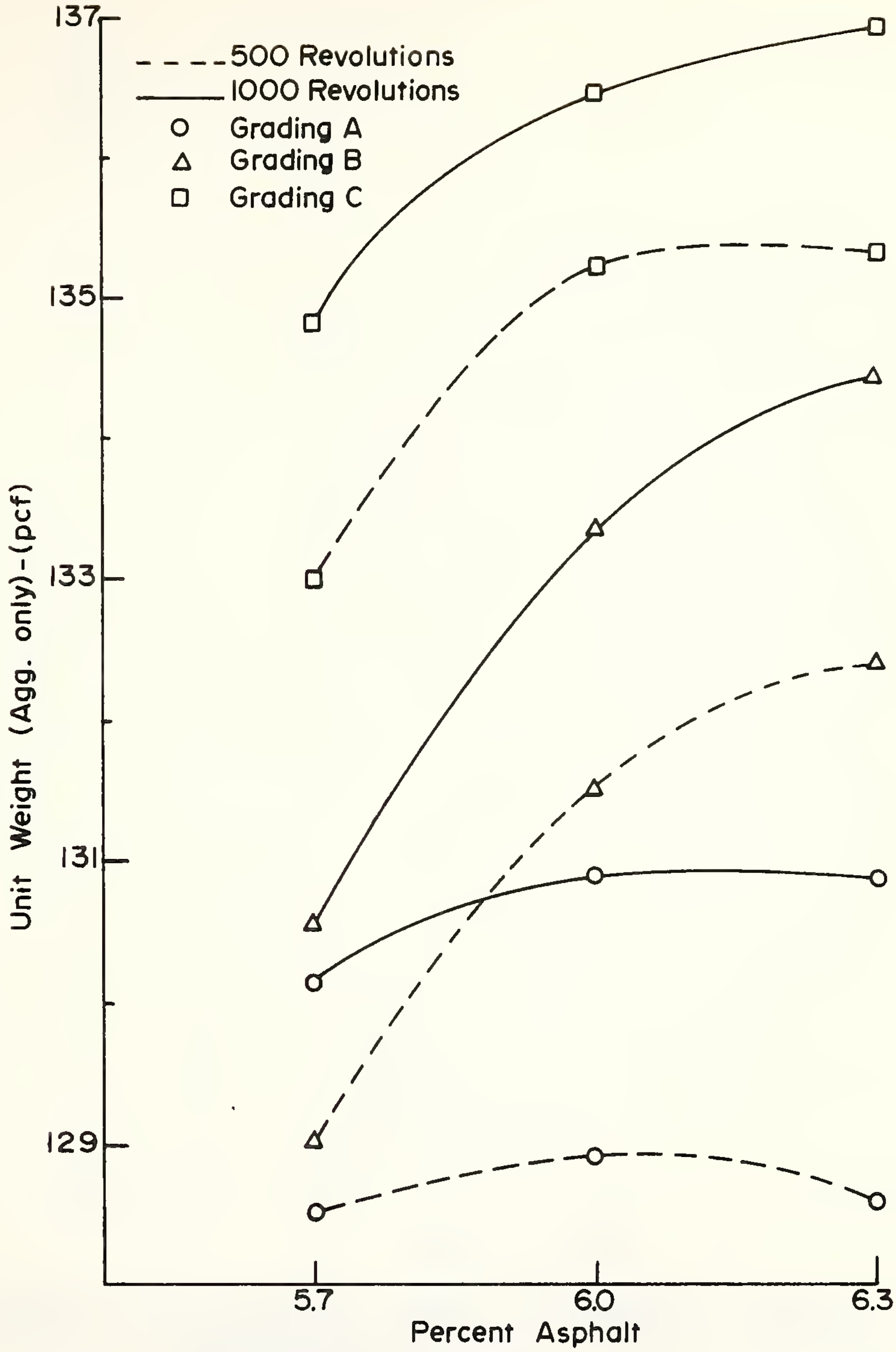


FIGURE 24 - UNIT WEIGHT (AGGREGATE ONLY) Vs. PERCENT ASPHALT FOR LIMESTONE MIXTURES AT TWO LEVELS OF DENSIFICATION.

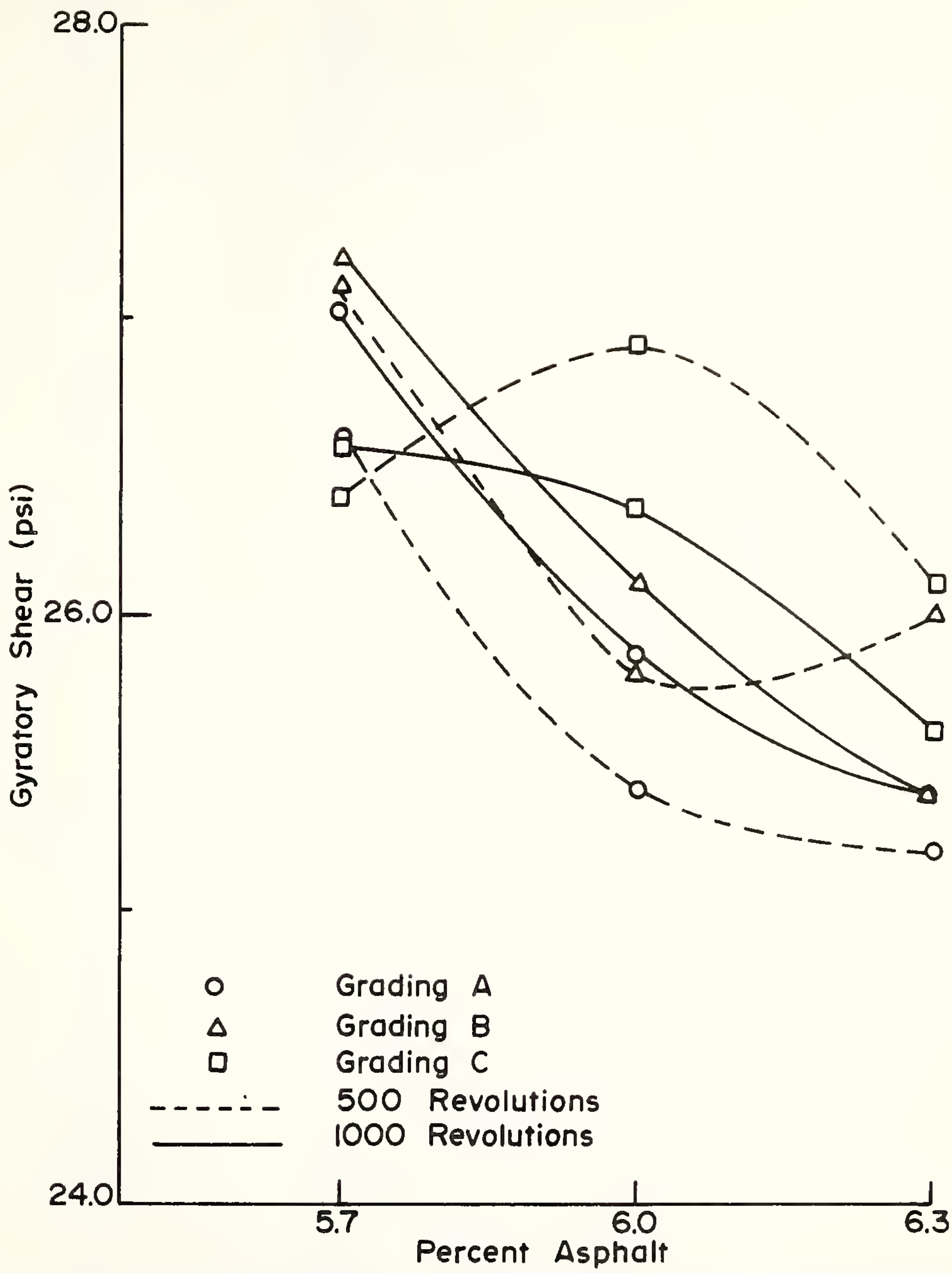


FIGURE 25 - GYRATORY SHEAR Vs. PERCENT ASPHALT FOR LIMESTONE MIXTURE AT TWO LEVELS OF DENSIFICATION.

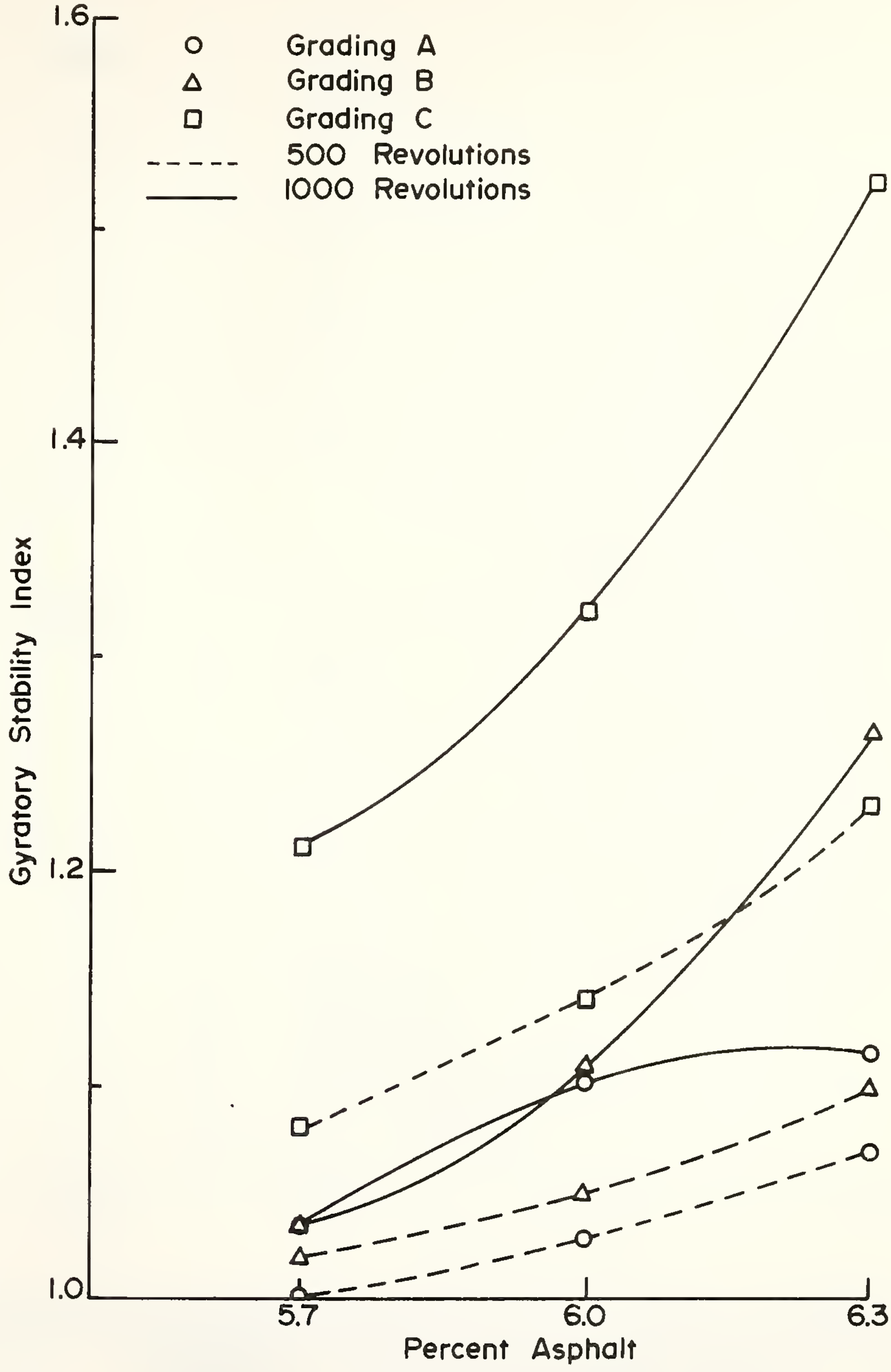


FIGURE 26 - GYRATORY STABILITY INDEX (GSI^{x}_{50}) Vs. PERCENT ASPHALT FOR LIMESTONE MIXTURES AT TWO LEVELS OF DENSIFICATION.

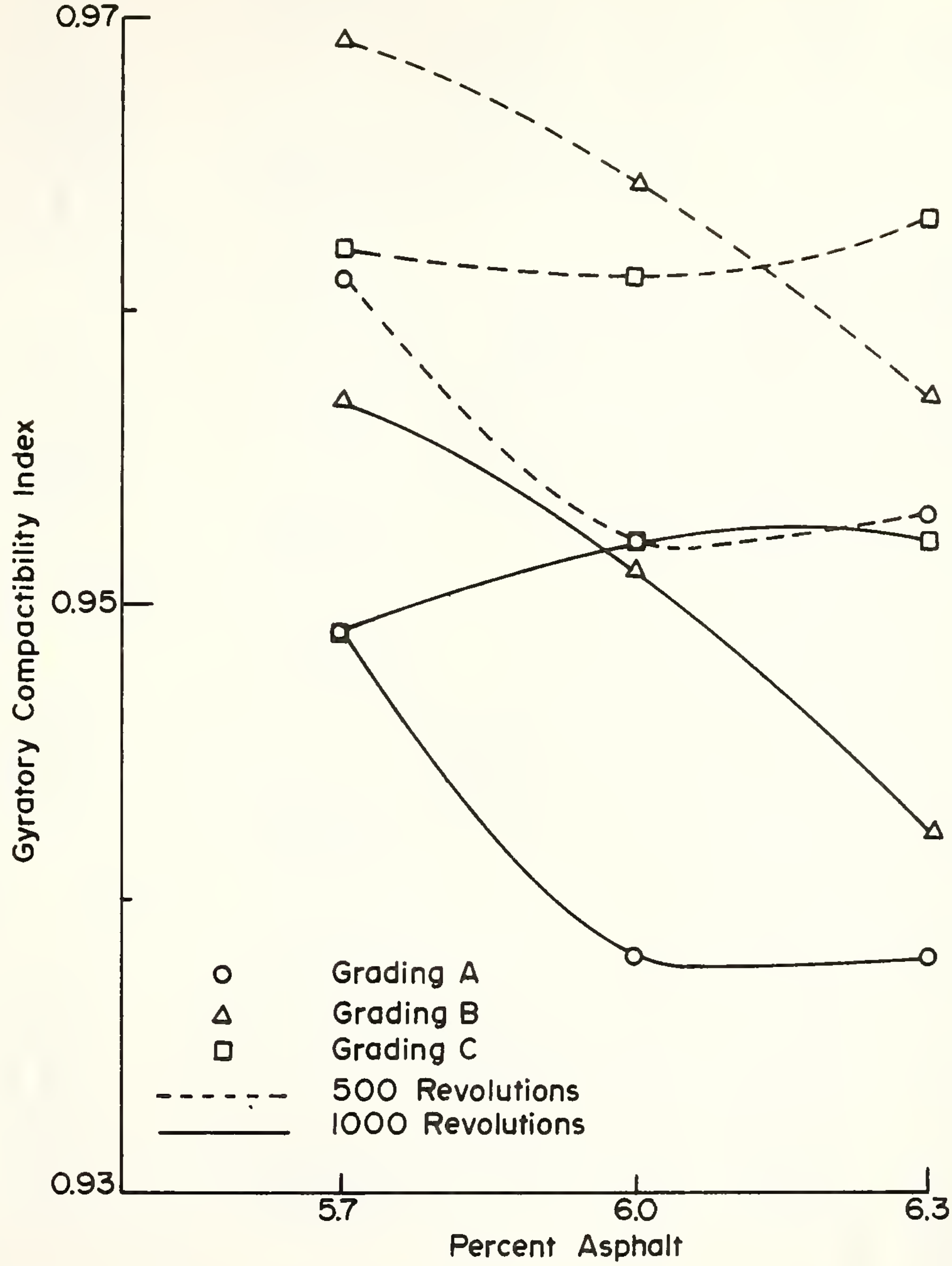
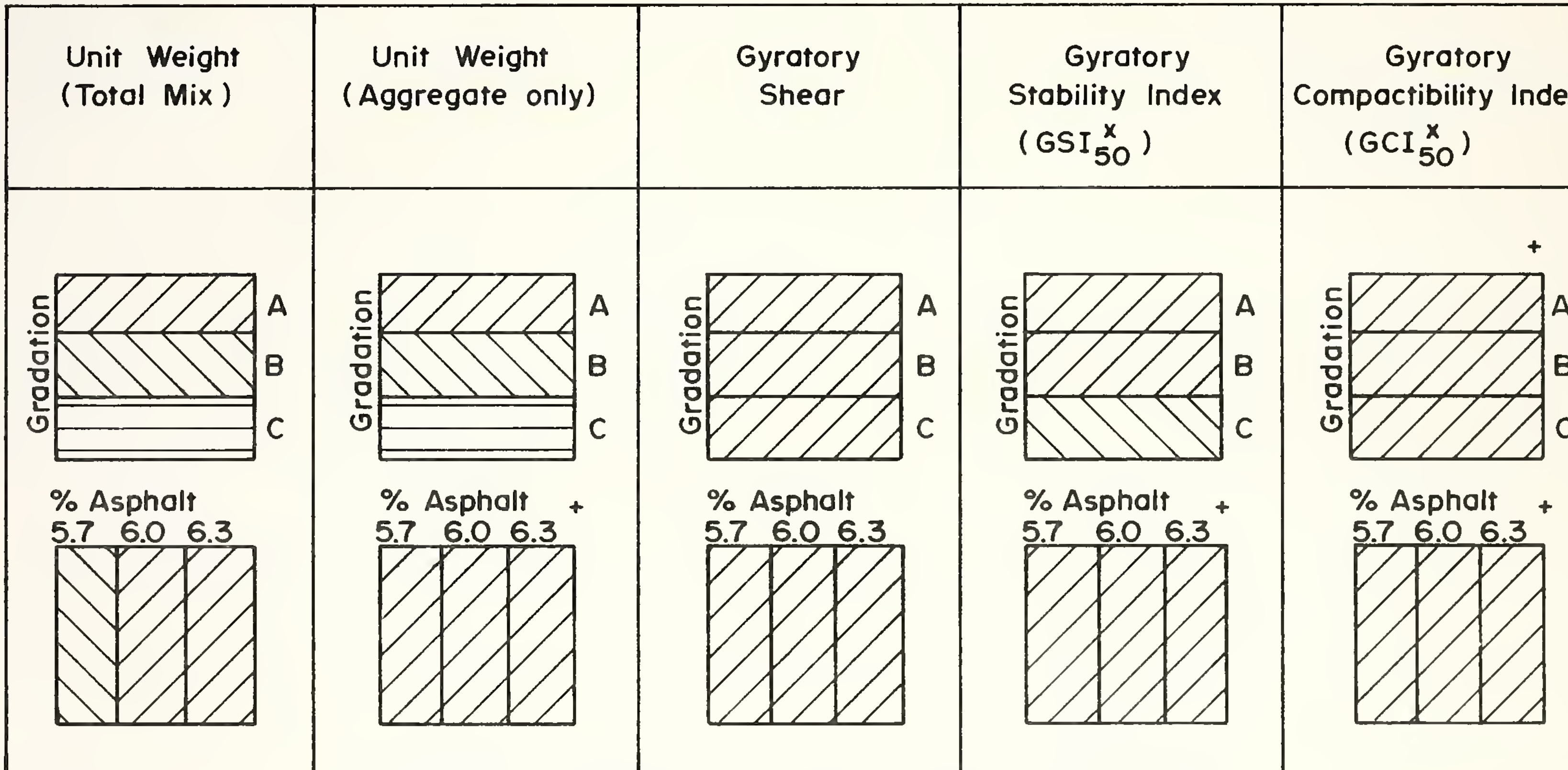


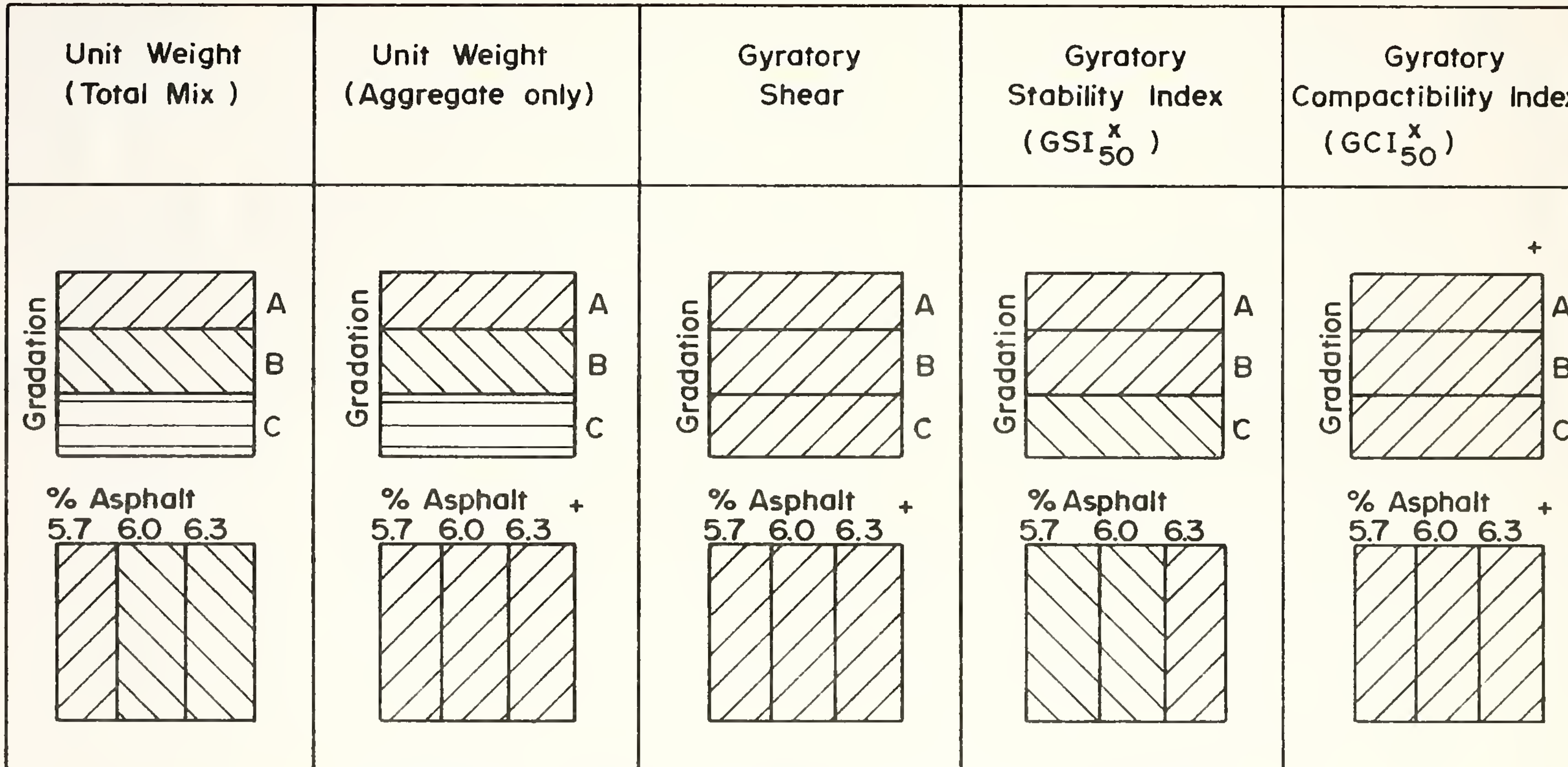
FIGURE 27- GYRATORY COMPACTIBILITY INDEX (GCI^{x}_{50}) Vs. PERCENT ASPHALT FOR LIMESTONE MIXTURES AT TWO LEVELS OF DENSIFICATION.



+ Significance between the means could not be ranked

NOTE : Difference in values between specimens incorporating the same symbol are not significant at 5% level, for each mixture property.

FIGURE 28 - NEWMAN-KEULS SEQUENTIAL RANGE TEST RESULTS (5% LEVEL) FOR LIMESTONE MIXTURE PROPERTIES (AT 500 REVOLUTIONS).



+Significance between the means could not be ranked

NOTE : Difference in values between specimens incorporating the same symbol are not significant at 5% level, for each mixture property.

FIGURE 29 - NEWMAN-KEULS SEQUENTIAL RANGE TEST RESULTS (5% LEVEL) FOR LIMESTONE MIXTURE PROPERTIES (AT 1000 REVOLUTIONS).

not significant (Figures 26, 28 and 29). The values were not significantly affected by using 5.7 percent asphalt content.

The above analysis on limestone mixtures indicates that the use of gradation C instead of gradation B will result in significant gain in unit weight (total mix and aggregate only) with a loss in stability at both 500 and 1000 revolutions. On the other hand, the use of gradation A will produce a loss in unit weight (total mix and aggregate only) without any gain in stability at both 500 and 1000 revolutions. This shows that strict control of gradation should be exercised. Use of 6.3 percent asphalt content instead of 6.0 percent will result in loss in stability at higher densification effort (1000 revolutions) without any gain in other properties. If 5.7 percent asphalt content is used, loss in unit weight (total mix) will result without any gains elsewhere. This indicates that leniency in control can be exercised towards the higher side of the asphalt content only in cases when traffic intensity is low. A strict check should be made on the lower side of the designed value since the use of less asphalt (within job mix tolerances) has no advantage.

Analyzing gravel mixtures (Figures 30, 31, 35 and 36), the use of gradation A instead of gradation B resulted in significant loss in unit weight (total mix and aggregate only) at 500 revolutions. This loss was not appreciable

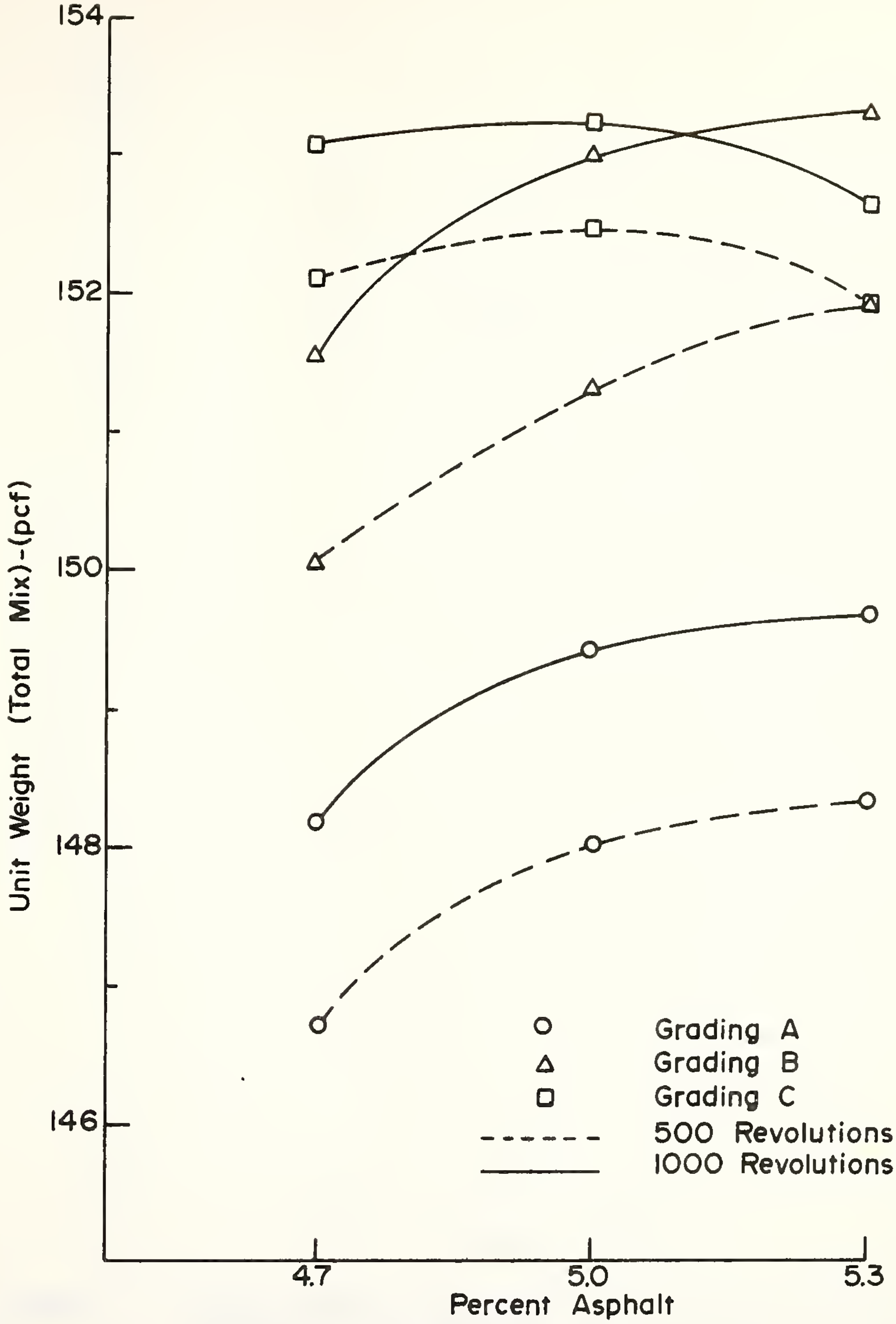


FIGURE 30 - UNIT WEIGHT (TOTAL MIX) Vs. PERCENT ASPHALT FOR GRAVEL MIXTURES AT TWO LEVELS OF DENSIFICATION.

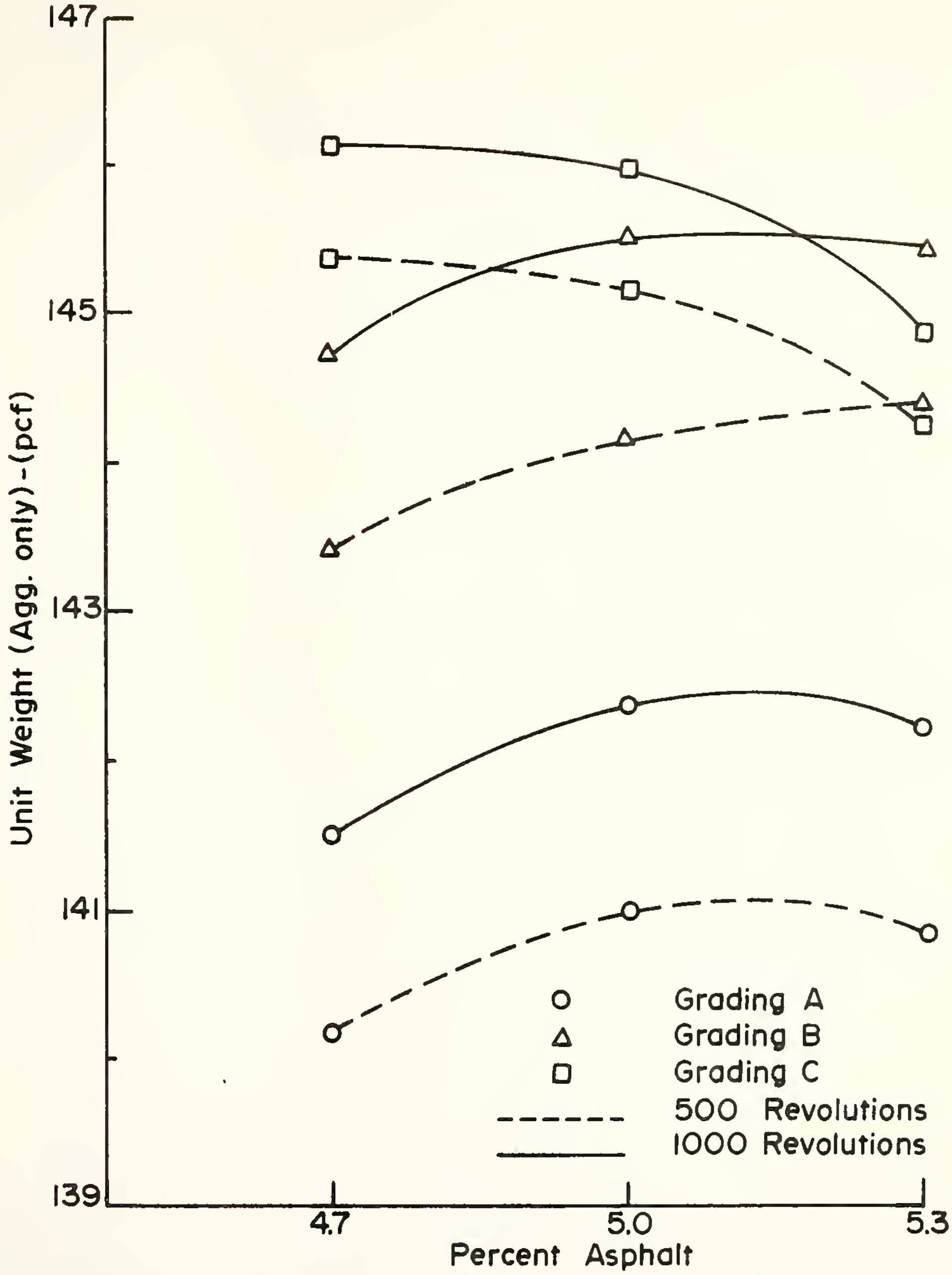


FIGURE 31 - UNIT WEIGHT (AGGREGATE ONLY) Vs. PERCENT ASPHALT FOR GRAVEL MIXTURES AT TWO LEVELS OF DENSIFICATION.

for unit weight (aggregate only) at 1000 revolutions. The unit weight (total mix and aggregate only) values were not appreciably affected at both 500 and 1000 revolutions when gradation C was used. Use of 4.7 percent or 5.3 percent asphalt content did not indicate any significant change in unit weight (total mix and aggregate only) values at 500 and 1000 revolutions.

The gyratory shear results (Figures 32 and 35) indicated that at 500 revolutions, the value for the specimen B5.0 was not significantly different from the values for specimens A5.0, A5.3 and B4.7, but significance was observed with respect to specimens A4.7, B5.3, C4.7, C5.0 and C5.3. Out of these, only specimens A4.7 and C4.7 had values higher than that for specimen B5.0. At the 1000 revolution level of densification, only specimens B5.3, C5.0 and C5.3 gave results significantly lower than specimen B5.0 (Figures 32 and 36). For the gyratory stability index results at 500 revolutions (Figures 33 and 35), only specimen A5.3 gave results not significantly different from B5.0. Appreciably higher values were observed for specimens B5.3, C5.0 and C5.3. The rest of the specimens gave values lower than specimen B5.0. The same trend was observed at 1000 revolutions (Figures 33 and 36) except for specimen C5.0 whose results were not significantly different from specimen B5.0. The gyratory compactibility index results indicated (Figures 34 and 35) that at 500 revolutions only specimen C5.3 gave values significantly higher than specimen B5.0. At 1000

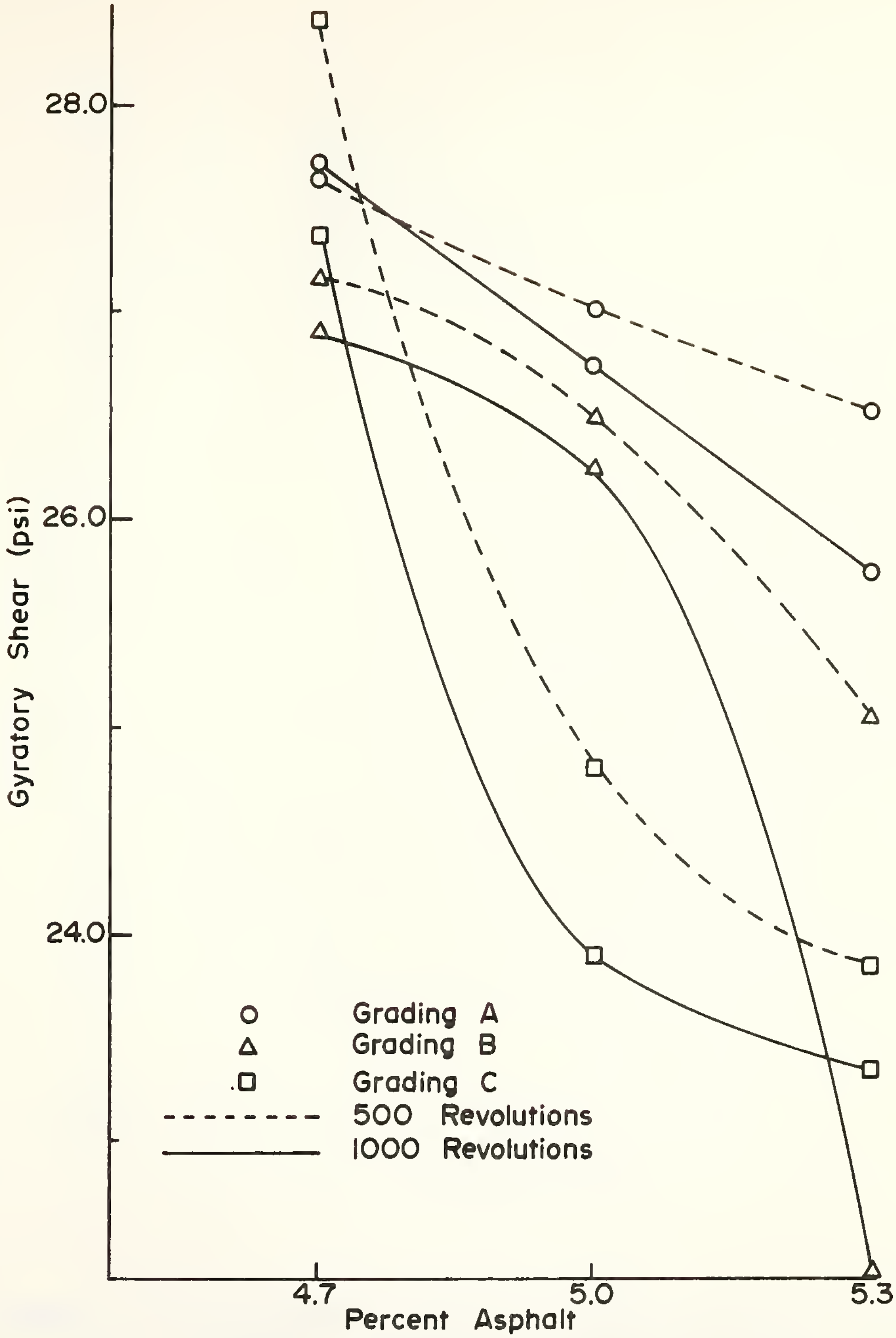


FIGURE 32 - GYRATORY SHEAR Vs. PERCENT ASPHALT FOR GRAVEL MIXTURES AT TWO LEVELS OF DENSIFICATION.

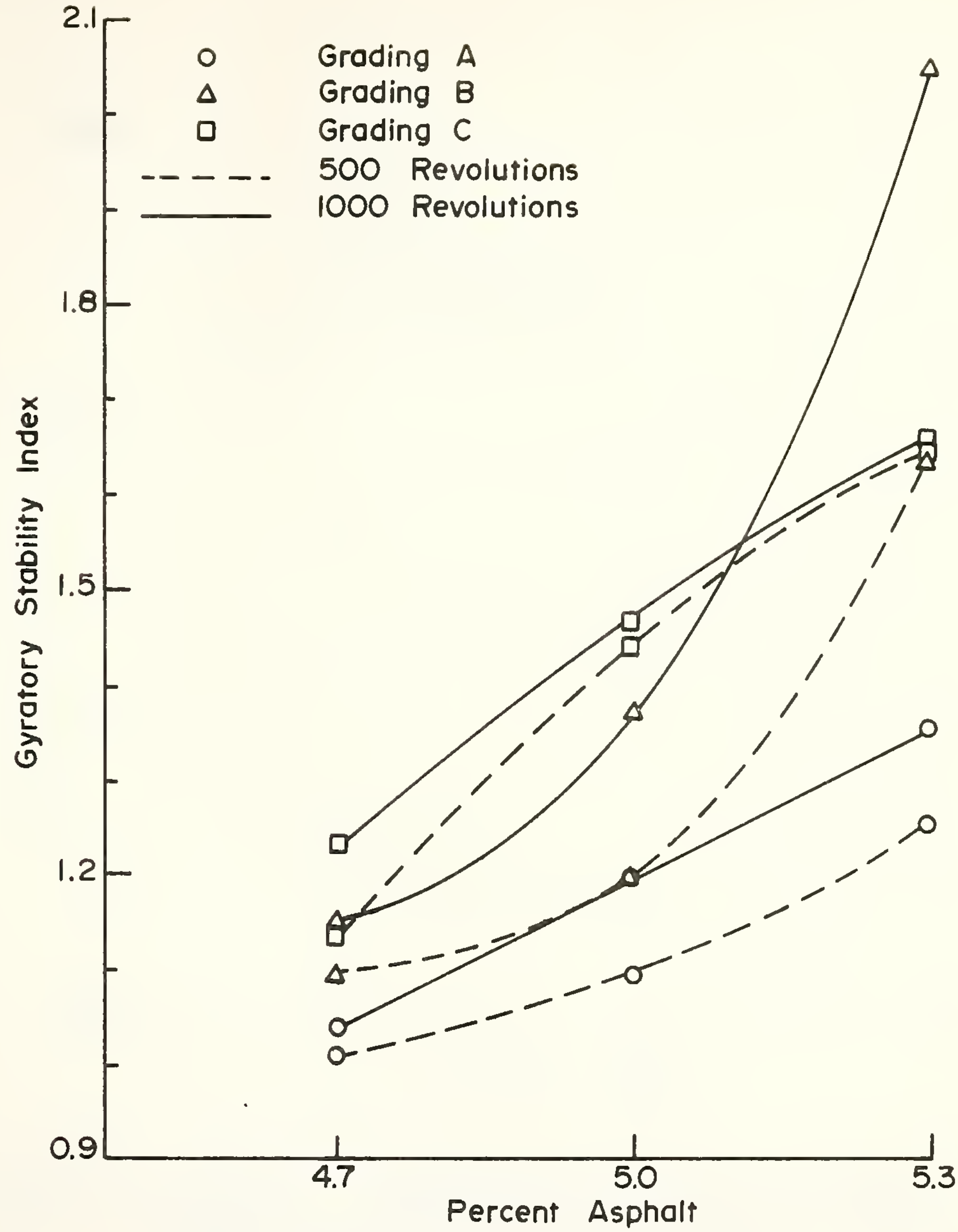


FIGURE 33 - GYRATORY STABILITY INDEX (GSI^{x}_{50}) Vs. PERCENT ASPHALT FOR GRAVEL MIXTURES AT TWO LEVELS OF DENSIFICATION.

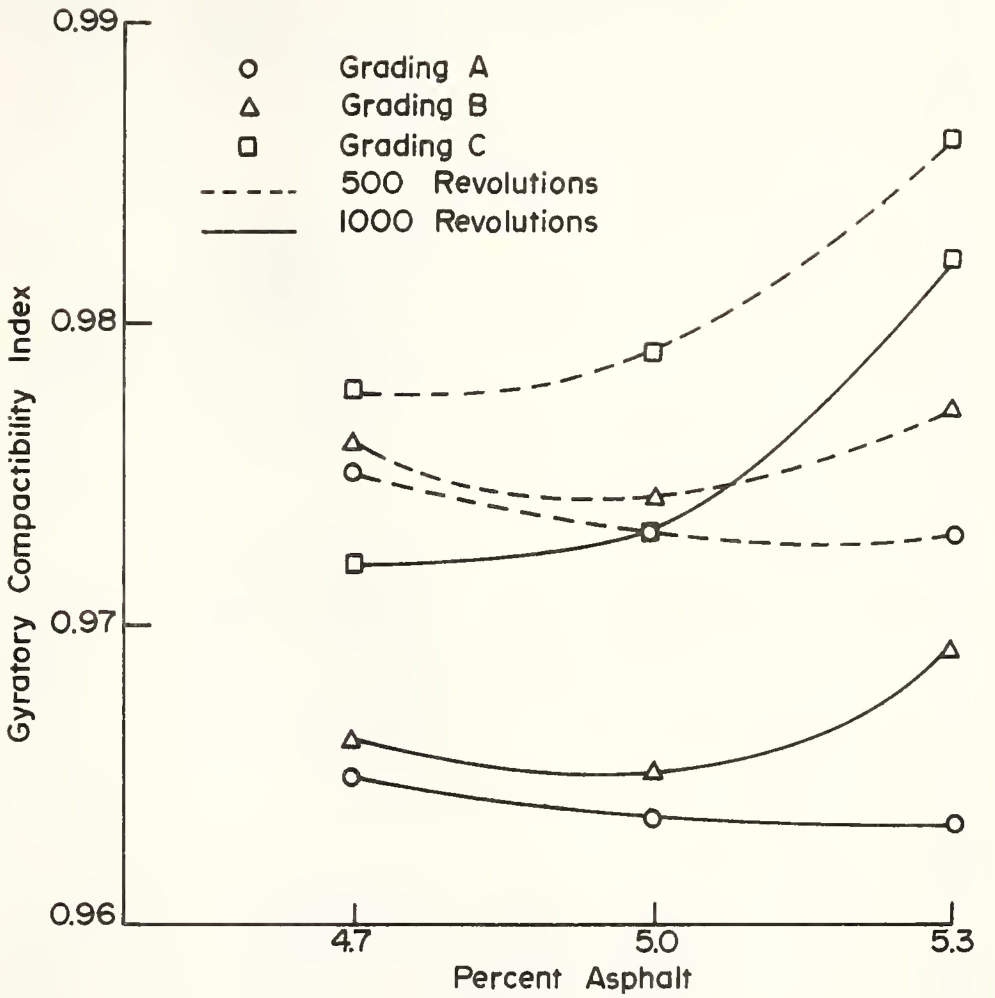
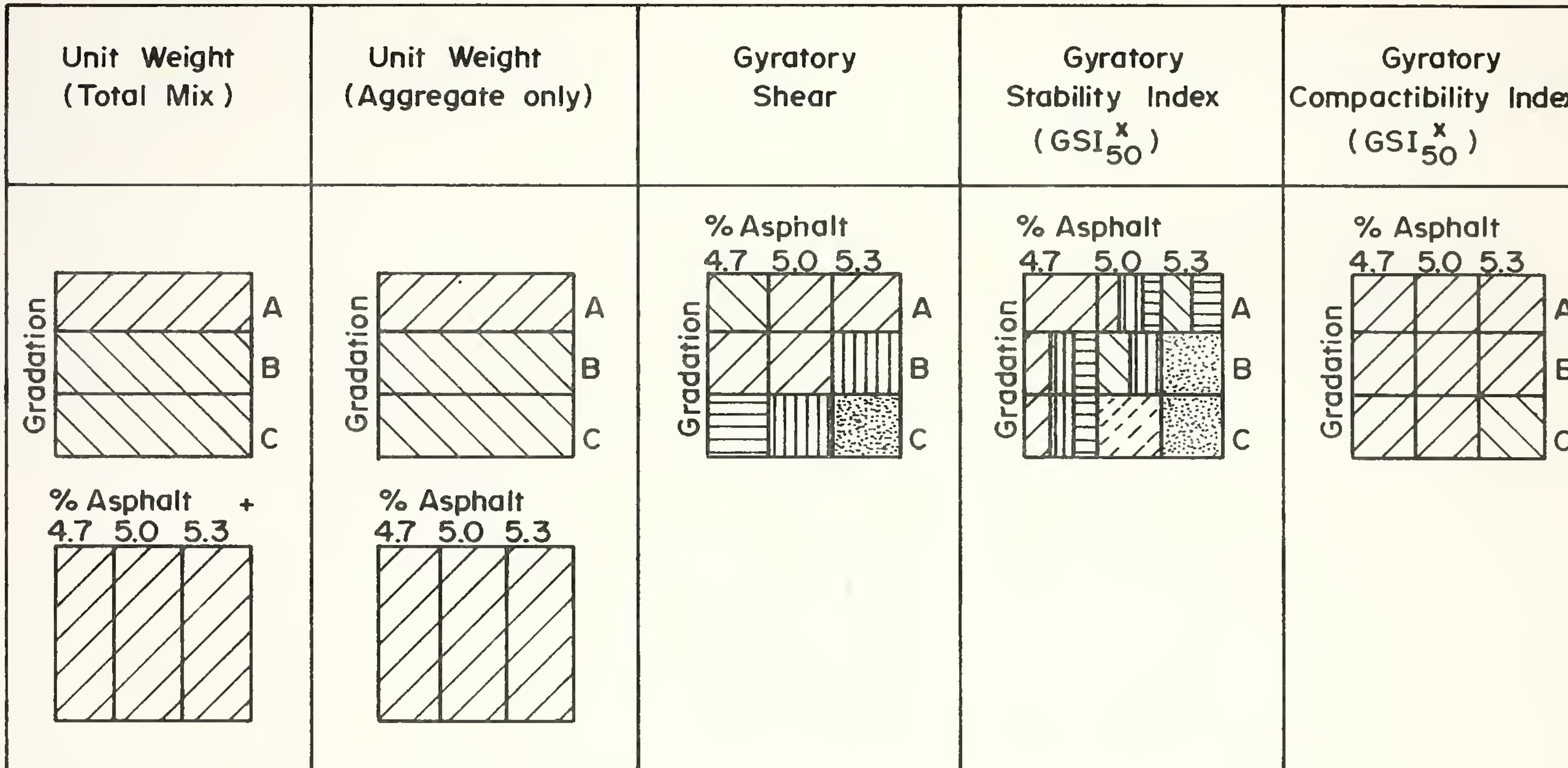


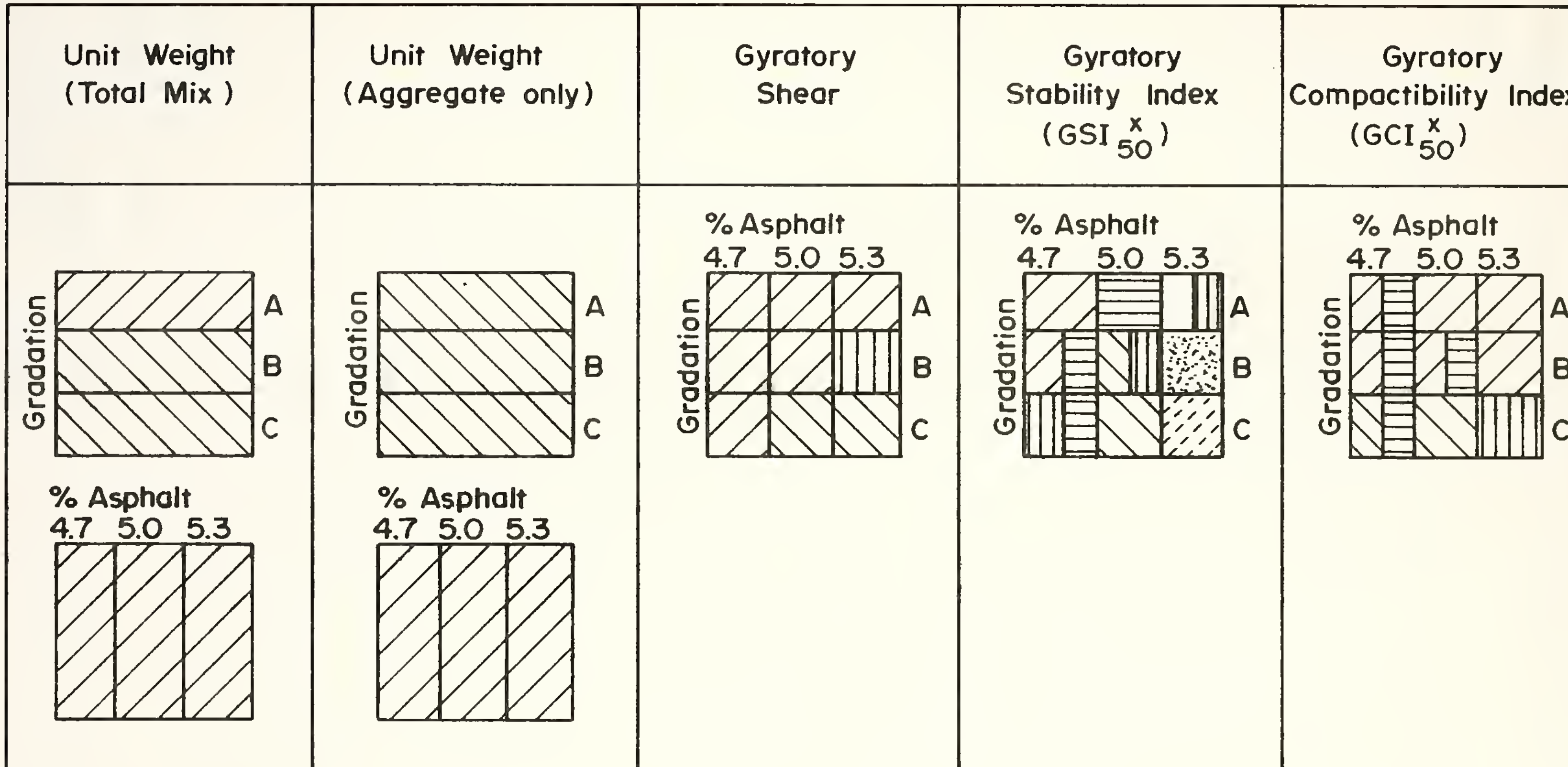
FIGURE 34 - GYRATORY COMPACTIBILITY INDEX (GCI_{50}^{x}) Vs. PERCENT ASPHALT FOR GRAVEL MIXTURES AT TWO LEVELS OF DENSIFICATION.



+ Significance between the means could not be ranked

NOTE : Difference in values between specimens incorporating the same symbol are not significant at 5% level, for each mixture property.

FIGURE 35 - NEWMAN - KEULS SEQUENTIAL RANGE TEST RESULTS (5% LEVEL) FOR GRAVEL MIXTURE PROPERTIES (AT 500 REVOLUTIONS).



NOTE : Difference in values between specimens incorporating the same symbol are not significant at 5% level, for each mixture property.

FIGURE 36 - NEWMAN - KEULS SEQUENTIAL RANGE TEST RESULTS (5% LEVEL) FOR GRAVEL MIXTURE PROPERTIES (AT 1000 REVOLUTIONS).

revolutions, specimens C4.7 and C5.0 also became significantly different from specimen B5.0 and gave higher values (Figures 34 and 36).

Examining the gravel mixtures, based on the above analysis, it can be observed that at low densification the use of the finer side of the designed gradation will result in loss in stability (except for the mixture combination C4.7) and loss in shear strength without any appreciable gain in the unit weight (total mix and aggregate only). Increase in densification will not result in any appreciable change in shear values for the mixture combination C4.7 and in stability values for the mixture combinations C4.7 and C5.0. Therefore under all circumstances a strict control should be exercised on the finer side of the designed gradation. Use of the coarser side of the designed gradation at low densifying effort (500 revolutions) will result in loss in unit weight (total mix and aggregate only) without any appreciable increase in shear strength (except for mixture combination A4.7), but the stability of the mixture will be improved (except for mixture combination A5.3). With increase in densifying effort (1000 revolutions), there is gain in unit weight (aggregate only) but the shear strength is reduced. The stability value remains unaffected. This indicates that leniency may be exercised on the coarser side if higher stability is desired.

Use of asphalt on the higher side of the designed value will not give any improved unit weight (total mix and aggregate only) but will result in loss of shear strength (except for mixture combination A5.3) and loss in stability (except for mixture combination A5.3). This indicates that strict control should be exercised on the higher side of the designed asphalt content. In case the quantity of asphalt used is on the lower side of the designed value, no appreciable loss in unit weight (total mix and aggregate only) will result but the shear strength (except for mixture combination B4.7) and stability (except for mixture combinations B4.7 and C4.7) of the mixture will improve at low densification levels (500 revolutions). With increased densification effort (1000 revolutions), the shear strength will be reduced. So leniency in control on the lower side of the designed asphalt content should only be exercised when high stability is desired.

The above analysis indicates that the gyratory testing machine is sensitive enough to study the changes in mixture properties caused by small variations in gradation and asphalt content.

Evaluation of the Design Method

Limestone and gravel mixes were designed for gradation B (Figure 3) as described earlier under the heading 'Bituminous Mixture Design'. The ASTM testing method (1) was followed to obtain the mixture properties which were later interpreted (author's own interpretation) to obtain the design asphalt content. Values of 6.0 percent and 5.0

percent were selected to be the design asphalt content for limestone and gravel mixes, respectively. In this section, an analysis is made to demonstrate if the selected design values were appropriately chosen for both limestone and gravel mixes. The analysis is based on the test results obtained by subjecting gradation B limestone and gravel mixes to the tolerance limits of $\pm$ 0.3 percentage points of asphalt. Accordingly, the properties of the limestone mixes having compositions B5.7, B6.0, B6.3 and gravel mixes having compositions B4.7, B5.0, B5.3 obtained earlier (under heading 'Mixture Property Calculations') were utilized in this study. Two levels of densification, one at 500 revolutions and the other at 1000 revolutions were selected and the property values of the specimens were compared at each level of densification.

Examining test results for limestone mixtures first, analysis of variance test results (Table 14) show all the mix property values, except gyratory shear, to be significantly affected due to variations in asphalt content at 500 revolutions. The test at 1000 revolutions indicated all the test values to be significantly different. Therefore, all the plots were studied except the gyratory shear plot at 500 revolutions.

Examining the unit weight (total mix) property plot (Figure 23) for 500 and 1000 revolutions, the difference between the values for limestone specimens B6.0 and B6.3

is much less as compared to the difference between B5.7 and B6.0. This indicates that reduction in asphalt quantity to 5.7 percent will not result in appreciable loss in unit weight. This is supported by NKSRT results (Figures 28 and 29) which show that the difference in the values of specimens with 6.0 percent and 6.3 percent asphalt content are not significant but both give values significantly different to the specimen having 5.7 percent asphalt. The same trend as in unit weight (total mix) is also observed in unit weight (aggregate only) plot (Figure 24). NKSRT results for this property (Figures 28 and 29) do not show any significant difference between the limestone specimens having 5.7 percent, 6.0 percent and 6.3 percent asphalt.

Examining the gyratory shear plot (Figure 25) for 1000 revolutions, the difference in values between the limestone specimens having specifications B6.0 and B6.3 is less as compared to the difference between the specimens B5.7 and B6.0. These differences seem to be of small magnitude as they were not detected by NKSRT (Figure 29).

The gyratory stability index plot (Figure 26) shows the difference between the values for limestone specimens B6.0 and B6.3 at 500 revolutions to be very small. The same is observed for specimens B5.7 and B6.0. This is supported by NKSRT results (Figure 28) because the test showed the differences between the specimens to be insignificant. At 1000 revolutions, the plot (Figure 26) shows considerable loss in stability for the specimen B6.3 as compared to specimens B6.0 and B5.7. The same analysis is made by NKSRT which shows (Figure 29) that the limestone specimens with 5.7 percent and 6.0 percent asphalt are not significantly different from each other with respect to the gyratory stability index property, but each of them is different from the specimen containing 6.3 percent asphalt.

Finally, looking at the gyratory compactibility index plot (Figure 27) the difference between values for limestone specimens B6.0 and B6.3 is almost the same as between B5.7 and B6.0 for both 500 and 1000 revolutions. The NKSRT could not detect the difference (Figures 28 and 29), i.e., the specimens B5.7, B6.0 and B6.3 are not significantly different from each other with respect to this property.

Examining the overall picture for limestone mixes, if asphalt content is increased from 6.0 percent to 6.3 percent, there is no significant gain in unit weight (total mix and aggregate only), but the loss in stability is appreciable. By reducing the asphalt content to 5.7 percent, there will be no gains whatsoever. Hence, it can be concluded that 6.0 percent asphalt is the correct optimum asphalt content for the limestone mixture design.

For evaluating gravel mixture design, analysis of variance test results show (Table 15) that the difference in values between specimens B4.7, B5.0 and B5.3 are not significant for unit weight (total mix) at 1000 revolutions and unit weight (aggregate only) at 500 and 1000 revolutions.

Therefore, all plots except the 1000 revolution plot in Figure 30 and 500 and 1000 revolution plots in Figure 31 were studied for analysis. The NKSRT results are presented in Figures 35 and 36.

Examining the unit weight (total mix) plot for 500 revolutions (Figure 30), the difference between values for gravel specimens B5.0 and B5.3 is small and so is the difference between values for specimens B4.7 and B5.0. The NKSRT could not detect any difference between these three specimens for the unit weight (total mix) property. This implies that the unit weight (total mix) value of all the three gravel specimens is almost the same. See Figures 35 and 36.

The difference in gyratory shear value (Figure 32) between the gravel specimens B5.0 and B5.3 appears to be more than the difference between the specimens B4.7 and B5.0 at 500 revolutions. The difference between the specimens B5.0 and B5.3 becomes quite appreciable at 1000 revolutions. These observations are supported by the NKSRT results (Figures 35 and 36) at both 500 and at 1000 revolutions. These results show that the values at 4.7 percent and 5.0 percent asphalt are nearly the same, but each of them is significantly different from the specimen having 5.3 percent asphalt.

The gyratory stability index plot (Figure 33) indicates that the difference between the values of gravel specimens B5.3 and B5.0 is appreciably higher as compared to the difference between the specimens B4.7 and B5.0 at both 500 and 1000 revolutions. The NKSRT results for 500 revolutions (Figure 35) show that the specimen B5.3 gave values significantly different as compared to specimen B4.7 or specimen B5.0. The difference between values for specimens B4.7 and B5.0 was not significant. At 1000 revolutions (Figures 36) all three gravel specimens gave values significantly different from each other.

The gyratory compactibility index values of gravel specimens B4.7, B5.0 and B5.3 do not appear to be significantly different from each other at both 500 and 1000 revolutions (Figure 26). This is supported by the NKSRT results (Figures 35 and 36).

In short, this analysis for gravel mixes indicates that increase in asphalt content from 5.0 percent to 5.3 percent will reduce the shear value and will result in loss of stability with no increase in unit weight. Decreasing the asphalt content to 4.7 percent has no advantage except that there will be a small gain in stability after a long period of simulated traffic densification. Thus 5.0 percent asphalt content as the optimum design value appears to be justified for the gravel mixture.

The above analysis for both limestone and gravel mixes demonstrates that 1) the tentative ASTM testing method (1) produces compaction and shear strain properties which can be used to design both limestone and gravel mixes, 2) the author's interpretation of the mixture properties as applied to the design of bituminous mixtures seems justified, and 3) the gyratory testing machine can be used successfully to design bituminous mixes.

CONCLUSIONS

These conclusions are based on the results of the experimental data and their discussion as presented. It should be noted that the conclusions given here are applicable to the materials and the testing procedures of this specific research only and may not be extended beyond these limits without the appropriate verification.

1. Bituminous mixtures can be effectively designed based on their compaction and shear strain properties obtained by means of the gyratory testing machine using the tentative ASTM testing method.
2. The gyratory testing machine can be used as a laboratory traffic simulation device to measure changes in compaction and shear strain properties of bituminous mixtures to be expected when they are placed in service.
3. The sensitivity of bituminous mixtures with respect to variations in gradation and asphalt content can be studied through the use of the gyratory testing machine. This in turn can help modify the job mix formula tolerances to suit particular field conditions.

SUGGESTIONS FOR FURTHER RESEARCH

Since the results show that the gyratory testing machine can be used successfully to design and evaluate bituminous mixes, it would now seem worthwhile to correlate the number of gyratory revolutions with equivalent single wheel loads. This can be accomplished by matching the mixture properties obtained by using different combinations of ram pressure, type of upper roller, roller pressure, gyratory angle and number of revolutions with the road mixture properties under given conditions of traffic.

Another possible study could be to include simulated weathering effects of the compacted specimen along with the simulated traffic densification. Since asphalt hardens due to weathering as time passes, incorporation of weathering effects would make the evaluation more realistic.

Since the gyratory testing machine is sensitive enough to differentiate mixture property values with good precision even for slight variations in mixture composition, work can be done to study the influence of aggregate and asphalt characteristics on the mixture properties when subjected to simulated traffic densification. This can possibly lead to a modified job mix formula concept and tolerances which will take into account all of the composition variables that

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APPENDICES

APPENDIX A

COMPUTER PROGRAM FOR TEST DATA

```
      PROGRAM MAIN(INPUT,OUTPUT,PUNCH)
C     KUM.
      REAL K,P
      INTEGER X,Z
      DIMENSION A(5,7,2),AV(7),STD(7),CV(7)
      DO 13 J=1,2
      READ 101,W,D,B,C
      DO 12 I=1,7
      READ 101,H,P,Y
  101 FORMAT (7F10.0)
      SI=Y/B
      GS=2.1*P/H
      WM=W*0.303/H
      WA=WM/(1.+D)
      CI=C/WM
      A(1,I,J)=SI
      A(2,I,J)=GS
      A(3,I,J)=WM
      A(4,I,J)=WA
      A(5,I,J)=CI
   12 CONTINUE
   13 CONTINUE
      Z=1
    6 X=0
      X=X+1
      IF(Z.GE.6)GO TO 99
      DO 10 I=X,7
      P=0.
      K=0.
      SUMP=0.
      SUMK=0.
      DO 10 J=1,2
      P=A(Z,I,J)
      K=A(Z,I,J)**2
      SUMP=SUMP+P
      SUMK=SUMK+K
      AV(I)=SUMP/2.
      STD(I)=SQRT(((2.*SUMK)-(SUMP**2))/2.)
      CV(I)=(STD(I)/AV(I))*100.
   10 CONTINUE
      PRINT 25
   25 FORMAT(1H1,'        '//////)
      PRINT 20,((A (Z,I,J),J=1,2),AV(I),STD(I),CV(I),I=1,7)
      PUNCH 27,((A(Z,5,J),A(Z,7,J)),J=1,2)
   27 FORMAT(F10.3)
   20 FORMAT (10X,2F10.3,10X,F10.3,5X,2F10.3,/)
      Z=Z+1
      GO TO 6
   99 STOP
      END
```

APPENDIX B

TEST RESULTS

Table 16. Compaction and Shear Strain Properties of Limestone Mixtures - Unit Weight (Total Mix)

Number of Revolutions	Specimen Number	Grading A % Asphalt			Grading B % Asphalt			Grading C % Asphalt		
		5.7	6.0	6.3	5.7	6.0	6.3	5.7	6.0	6.3
50	1	132.2	131.4	129.6	132.8	134.9	135.0	136.3	138.4	138.5
	2	129.0	128.8	130.8	131.4	134.0	134.3	134.3	137.0	138.4
	Av.	130.6	130.1	130.2	132.1	134.4	134.6	135.3	137.7	138.5
100	1	133.3	133.2	131.1	133.8	136.1	136.7	137.7	140.0	139.9
	2	130.7	130.6	132.6	132.6	135.3	135.9	135.6	138.6	139.8
	Av.	132.0	131.9	131.8	133.2	135.7	136.3	136.6	139.3	139.9
200	1	134.6	135.1	133.0	134.9	137.6	138.4	139.4	141.7	141.5
	2	132.6	132.6	134.6	133.9	136.8	137.8	137.0	140.4	141.4
	Av.	133.6	133.9	133.8	134.4	137.2	138.1	138.2	141.0	141.5
300	1	135.4	136.4	134.2	135.7	138.4	139.6	140.4	142.7	142.4
	2	133.7	133.9	135.8	134.9	137.7	138.9	138.0	141.3	142.4
	Av.	134.6	135.1	135.0	135.3	138.1	139.2	139.2	142.0	142.4
500	1	136.6	137.8	135.8	136.6	139.7	141.1	141.7	143.9	144.1
	2	135.2	135.4	137.5	136.1	139.1	140.4	139.4	142.7	143.7
	Av.	135.9	136.6	136.7	136.3	139.4	140.7	140.6	143.3	143.9
750	1	137.4	139.0	137.1	137.4	140.6	142.3	142.9	144.9	145.3
	2	136.4	136.6	138.7	137.1	140.4	141.6	140.6	143.7	144.8
	Av.	136.9	137.8	137.9	137.3	140.5	141.9	141.8	144.3	145.1
1000	1	138.0	139.8	138.1	138.0	141.4	143.3	143.6	145.4	145.8
	2	137.1	137.6	139.6	137.9	141.2	142.4	141.4	143.8	145.3
	Av.	137.6	138.7	138.9	138.0	141.3	142.9	142.5	144.6	145.5

Table 17. Compaction and Shear Strain Properties of Limestone Mixtures - Unit Weight (Agg. Only)

Number of Revolutions	Specimen Number	Grading A % Asphalt			Grading B % Asphalt			Grading C % Asphalt		
		5.7	6.0	6.3	5.7	6.0	6.3	5.7	6.0	6.3
50	1	125.1	124.0	121.9	125.6	127.3	127.0	128.9	130.6	130.3
	2	122.1	121.5	123.0	124.3	126.4	126.3	127.0	129.3	130.2
	Av.	123.6	122.8	122.5	124.9	126.8	126.7	128.0	129.9	130.3
100	1	126.1	125.7	123.3	126.6	128.4	128.6	130.3	132.1	131.6
	2	123.6	123.2	124.7	125.4	127.6	127.8	128.2	130.7	131.6
	Av.	124.9	124.4	124.0	126.0	128.0	128.2	129.3	131.4	131.6
200	1	127.3	127.5	125.1	127.6	129.8	130.2	131.8	133.6	133.2
	2	125.5	125.1	126.6	126.7	129.0	129.6	129.6	132.4	133.0
	Av.	126.4	126.3	125.8	127.2	129.4	129.9	130.7	133.0	133.1
300	1	128.1	128.7	126.2	128.3	130.6	131.3	132.9	134.6	134.0
	2	126.5	126.3	127.8	127.6	129.9	130.7	130.6	133.3	133.9
	Av.	127.3	127.5	127.0	128.0	130.3	131.0	131.7	134.0	134.0
500	1	129.2	130.0	127.8	129.2	131.8	132.7	134.1	135.8	135.5
	2	127.9	127.8	129.3	128.8	131.3	132.1	131.9	134.6	135.2
	Av.	128.5	128.9	128.6	129.0	131.5	132.4	133.0	135.2	135.3
750	1	130.0	131.1	129.0	130.0	132.7	133.9	135.2	136.7	136.7
	2	129.0	128.9	130.5	129.7	132.4	133.2	133.0	135.6	136.2
	Av.	129.5	130.0	129.7	129.9	132.6	133.5	134.1	136.1	136.5
1000	1	130.6	131.9	130.0	130.6	133.4	134.8	135.9	137.2	137.1
	2	129.7	129.8	131.3	130.5	133.3	134.0	133.8	135.6	136.7
	Av.	130.2	130.8	130.6	130.5	133.3	134.4	134.8	136.4	136.9

Table 18. Compaction and Shear Strain Properties of Limestone Mixtures - Gyratory Shear

Number of Revolutions	Specimen Number	Grading A % Asphalt			Grading B % Asphalt			Grading C % Asphalt		
		5.7	6.0	6.3	5.7	6.0	6.3	5.7	6.0	6.3
50	1	25.2	23.6	23.6	26.5	25.1	24.3	25.1	25.5	25.4
	2	26.1	25.0	25.6	25.6	25.3	26.4	26.3	26.8	25.2
	Av.	25.7	24.3	24.6	26.1	25.2	25.4	25.7	26.2	25.3
100	1	25.4	23.9	23.7	26.9	25.3	24.6	25.4	25.8	25.6
	2	26.4	25.1	25.9	26.1	25.6	26.5	26.6	27.1	25.5
	Av.	25.9	24.5	24.8	26.5	25.5	25.6	26.0	26.5	25.5
200	1	25.6	24.3	23.8	27.1	25.4	24.7	25.7	25.9	25.9
	2	26.8	25.3	26.1	26.3	25.9	26.7	26.6	27.4	25.5
	Av.	26.2	24.9	25.0	26.7	25.6	25.7	26.2	26.7	25.7
300	1	25.8	24.5	24.1	27.3	25.6	24.9	25.7	25.9	26.1
	2	27.1	25.8	25.9	26.5	25.8	26.9	26.8	27.6	25.7
	Av.	26.4	25.1	25.0	26.9	25.7	25.9	26.3	26.8	25.9
500	1	26.0	24.8	24.2	27.5	25.8	25.0	25.9	26.1	26.2
	2	27.4	26.1	26.3	26.8	25.9	27.0	26.9	27.7	26.0
	Av.	26.7	25.4	25.2	27.1	25.8	26.0	26.4	26.9	26.1
750	1	26.2	25.0	24.2	27.4	25.8	24.7	25.9	26.3	26.0
	2	27.6	26.3	26.5	26.8	26.1	26.5	26.9	27.2	25.7
	Av.	26.9	25.6	25.3	27.1	25.9	25.6	26.4	26.8	25.8
1000	1	26.3	25.1	24.4	27.6	25.9	24.7	26.1	25.9	25.6
	2	27.8	26.5	26.5	26.9	26.3	26.0	27.1	26.8	25.6
	Av.	27.0	25.8	25.4	27.2	26.1	25.4	26.6	26.4	25.6

Table 19. Compaction and Shear Strain Properties of Limestone Mixtures - Gyratory Stability Index (GSI^{x}_{50})

Number of Revolutions	Specimen Number	Grading A % Asphalt			Grading B % Asphalt			Grading C % Asphalt		
		5.7	6.0	6.3	5.7	6.0	6.3	5.7	6.0	6.3
50	1	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
	2	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
	Av.	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
100	1	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.01
	2	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.02
	Av.	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.02
200	1	1.00	1.00	1.07	1.00	1.00	1.06	1.01	1.07	1.06
	2	1.00	1.00	1.07	1.00	1.00	1.04	1.04	1.00	1.07
	Av.	1.00	1.00	1.07	1.00	1.00	1.05	1.02	1.03	1.06
300	1	1.00	1.00	1.07	1.00	1.01	1.09	1.02	1.14	1.10
	2	1.00	1.03	1.07	1.00	1.01	1.06	1.05	1.02	1.10
	Av.	1.00	1.01	1.07	1.00	1.01	1.08	1.04	1.08	1.10
500	1	1.00	1.00	1.07	1.02	1.04	1.12	1.07	1.17	1.29
	2	1.00	1.07	1.07	1.02	1.06	1.09	1.09	1.10	1.17
	Av.	1.00	1.03	1.07	1.02	1.05	1.10	1.08	1.14	1.23
750	1	1.00	1.06	1.09	1.02	1.09	1.18	1.14	1.23	1.47
	2	1.01	1.09	1.10	1.02	1.09	1.18	1.18	1.17	1.36
	Av.	1.01	1.08	1.10	1.02	1.09	1.18	1.16	1.20	1.41
1000	1	1.03	1.12	1.11	1.04	1.11	1.25	1.19	1.34	1.63
	2	1.04	1.09	1.13	1.04	1.11	1.28	1.24	1.30	1.41
	Av.	1.04	1.10	1.12	1.04	1.11	1.27	1.21	1.32	1.52

Table 20. Compaction and Shear Strain Properties of Limestone Mixtures - Gyratory Compactibility Index (GCI^{x}_{50})

Number of Revolutions	Specimen Number	Grading A % Asphalt			Grading B % Asphalt			Grading C % Asphalt		
		5.7	6.0	6.3	5.7	6.0	6.3	5.7	6.0	6.3
50	1	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
	2	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
	Av.	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
100	1	.992	.987	.989	.992	.991	.988	.990	.989	.990
	2	.987	.986	.987	.991	.990	.988	.991	.989	.990
	Av.	.990	.986	.988	.992	.991	.988	.990	.989	.990
200	1	.983	.973	.975	.984	.981	.975	.978	.977	.979
	2	.973	.971	.972	.981	.980	.975	.981	.976	.979
	Av.	.978	.972	.973	.982	.980	.975	.979	.977	.979
300	1	.976	.964	.966	.979	.974	.967	.970	.970	.973
	2	.965	.962	.963	.974	.973	.966	.973	.969	.972
	Av.	.971	.963	.964	.976	.974	.967	.972	.970	.973
500	1	.968	.954	.954	.972	.966	.957	.962	.962	.962
	2	.954	.951	.951	.965	.963	.956	.963	.960	.964
	Av.	.961	.952	.953	.969	.964	.957	.962	.961	.963
750	1	.962	.946	.945	.966	.959	.949	.953	.955	.953
	2	.946	.943	.943	.958	.954	.949	.955	.953	.956
	Av.	.954	.944	.944	.962	.957	.949	.954	.954	.955
1000	1	.958	.940	.938	.962	.954	.942	.949	.952	.950
	2	.941	.936	.937	.953	.949	.943	.950	.953	.953
	Av.	.949	.938	.938	.957	.951	.942	.949	.952	.952

Table 21. Compaction and Shear Strain Properties of Gravel Mixtures - Unit Weight (Total Mix)

Number of Revolutions	Specimen Number	Grading A % Asphalt			Grading B % Asphalt			Grading C % Asphalt		
		4.7	5.0	5.3	4.7	5.0	5.3	4.7	5.0	5.3
50	1	143.6	144.6	145.2	146.4	147.4	148.9	148.7	149.0	150.0
	2	142.4	143.5	143.5	146.4	147.5	148.0	148.7	149.2	149.6
	Av.	143.0	144.1	144.3	146.4	147.5	148.4	148.7	149.1	149.8
100	1	144.5	145.5	146.4	147.3	148.4	149.8	149.8	150.0	150.7
	2	143.6	144.7	144.6	147.3	148.6	149.1	149.8	150.2	150.4
	Av.	144.0	145.1	145.5	147.3	148.5	149.5	149.8	150.1	150.5
200	1	145.7	146.7	147.6	148.5	149.4	150.9	150.8	151.0	151.3
	2	144.7	145.9	145.8	148.7	149.7	150.4	150.8	151.3	151.1
	Av.	145.2	146.3	146.7	148.6	149.5	150.7	150.8	151.1	151.2
300	1	146.3	147.7	148.2	149.2	150.2	151.8	151.4	151.6	151.7
	2	145.4	146.8	146.5	149.4	150.5	151.2	151.5	151.9	151.5
	Av.	145.9	147.3	147.4	149.3	150.3	151.5	151.4	151.7	151.6
500	1	147.1	148.6	149.3	149.9	151.1	152.0	152.2	152.2	152.0
	2	146.3	147.5	147.3	150.2	151.6	152.0	152.2	152.7	151.8
	Av.	146.7	148.1	148.3	150.0	151.3	152.0	152.2	152.4	151.9
750	1	147.9	149.4	150.3	150.7	151.9	152.7	152.7	152.6	152.3
	2	147.2	148.3	148.0	151.1	152.4	152.6	152.4	153.1	152.4
	Av.	147.6	158.9	149.1	150.9	152.2	152.6	152.6	152.9	152.3
1000	1	148.5	150.0	150.9	151.3	152.6	153.3	153.1	153.0	152.7
	2	147.8	148.8	148.4	151.8	153.1	153.0	152.9	153.5	152.4
	Av.	148.2	149.4	149.7	151.5	152.8	153.2	153.0	153.2	152.5

Table 22. Compaction and Shear Strain Properties of Gravel Mixtures - Unit Weight (Agg. Only)

Number of Revolutions	Specimen Number	Grading A % Asphalt			Grading B % Asphalt			Grading C % Asphalt		
		4.7	5.0	5.3	4.7	5.0	5.3	4.7	5.0	5.3
50	1	137.1	137.7	137.7	139.8	140.4	141.4	142.0	141.9	142.4
	2	136.0	136.7	136.3	139.9	140.5	140.6	142.0	142.1	142.1
	Av.	136.6	137.2	137.1	139.8	140.4	141.0	142.0	142.0	142.2
100	1	138.0	138.6	139.0	140.7	141.3	142.3	143.1	142.8	143.1
	2	137.1	137.9	137.3	140.7	141.5	141.6	143.1	143.0	142.8
	Av.	137.6	138.2	138.2	140.7	141.4	141.9	143.1	142.9	143.0
200	1	139.1	139.7	140.1	141.8	142.3	143.3	144.1	143.8	143.7
	2	138.1	139.0	138.4	142.0	142.6	142.8	144.0	144.1	143.5
	Av.	138.6	139.3	139.3	141.9	142.4	143.1	144.1	143.9	143.6
300	1	139.8	140.7	140.8	142.5	143.0	144.1	144.7	144.3	144.0
	2	138.9	139.8	139.1	142.7	143.3	143.6	144.7	144.6	143.9
	Av.	139.3	140.2	139.9	142.6	143.2	143.8	144.7	144.5	143.9
500	1	140.5	141.5	141.8	143.2	143.9	144.3	145.4	144.9	144.3
	2	139.8	140.5	139.9	143.4	144.3	144.3	145.4	145.4	144.1
	Av.	140.1	141.0	140.8	143.3	144.1	144.3	145.4	145.2	144.2
750	1	141.3	142.3	142.7	143.9	144.6	145.0	145.8	145.4	144.7
	2	140.6	141.3	140.5	144.3	145.2	144.9	145.6	145.8	144.6
	Av.	140.9	141.8	141.6	144.1	144.9	145.0	145.7	145.6	144.6
1000	1	141.8	142.9	143.3	144.5	145.3	145.6	146.2	145.7	145.0
	2	141.2	141.7	141.0	145.0	145.8	145.3	146.0	146.1	144.8
	Av.	141.5	142.3	142.2	144.7	145.6	145.5	146.1	145.9	144.9

Table 23. Compaction and Shear Strain Properties of Gravel Mixtures - Gyratory Shear

Number of Revolutions	Specimen Number	Grading A % Asphalt			Grading B % Asphalt			Grading C % Asphalt		
		4.7	5.0	5.3	4.7	5.0	5.3	4.7	5.0	5.3
50	1	27.2	26.7	27.1	26.8	26.3	26.2	28.2	27.7	27.5
	2	26.9	26.9	27.1	27.0	26.5	26.3	28.4	27.7	27.0
	Av.	27.0	26.8	27.1	26.9	26.4	26.3	28.3	27.7	27.2
100	1	27.3	26.9	27.1	27.0	26.5	26.2	28.1	27.2	26.9
	2	27.1	26.9	26.9	27.1	26.6	26.3	28.4	27.2	26.2
	Av.	27.2	26.9	27.0	27.1	26.5	26.2	28.3	27.2	26.6
200	1	27.6	26.9	26.9	27.0	26.6	25.9	28.3	26.4	25.4
	2	27.4	27.1	26.9	27.2	26.4	26.3	28.4	26.2	25.5
	Av.	27.5	27.0	26.9	27.1	26.5	26.1	28.4	26.3	25.4
300	1	27.7	26.8	26.8	27.1	26.5	25.6	28.5	25.8	24.6
	2	27.5	27.3	26.8	27.1	26.6	26.0	28.5	25.6	24.6
	Av.	27.6	27.1	26.8	27.1	26.6	25.8	28.5	25.7	24.6
500	1	27.8	26.8	26.5	27.0	26.5	25.4	28.4	24.8	23.9
	2	27.5	27.2	26.5	27.2	26.5	24.7	28.4	24.8	23.7
	Av.	27.6	27.0	26.5	27.1	26.5	25.0	28.4	24.8	23.8
750	1	28.0	26.7	26.2	26.9	26.4	24.1	28.0	24.1	23.7
	2	27.4	27.1	26.2	27.1	26.4	23.7	28.2	24.2	23.1
	Av.	27.7	26.9	26.2	27.0	26.4	23.9	28.1	24.2	23.4
1000	1	27.9	26.5	25.7	26.8	26.2	22.5	27.4	24.0	23.8
	2	27.5	27.0	25.8	27.0	26.3	22.3	27.3	23.8	22.9
	Av.	27.7	26.8	25.7	26.9	26.3	22.4	27.4	23.9	23.4

Table 24. Compaction and Shear Strain Properties of Gravel Mixtures - Gyratory Stability Index (GSI^{x}_{50})

Number of Revolutions	Specimen Number	Grading A % Asphalt			Grading B % Asphalt			Grading C % Asphalt		
		4.7	5.0	5.3	4.7	5.0	5.3	4.7	5.0	5.3
50	1	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
	2	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
	Av.	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
100	1	1.00	1.00	1.03	1.00	1.00	1.08	1.01	1.09	1.25
	2	1.00	1.00	1.03	1.00	1.00	1.08	1.01	1.09	1.29
	Av.	1.00	1.00	1.03	1.00	1.00	1.08	1.01	1.09	1.27
200	1	1.00	1.00	1.11	1.02	1.06	1.18	1.07	1.23	1.40
	2	1.00	1.02	1.09	1.02	1.07	1.17	1.03	1.23	1.47
	Av.	1.00	1.01	1.10	1.02	1.06	1.18	1.05	1.23	1.44
300	1	1.00	1.03	1.17	1.03	1.12	1.34	1.09	1.31	1.50
	2	1.00	1.02	1.14	1.07	1.13	1.26	1.06	1.32	1.61
	Av.	1.00	1.02	1.15	1.05	1.13	1.30	1.07	1.32	1.55
500	1	1.01	1.10	1.25	1.05	1.18	1.68	1.18	1.42	1.58
	2	1.02	1.09	1.24	1.12	1.21	1.58	1.08	1.44	1.70
	Av.	1.01	1.09	1.25	1.09	1.19	1.63	1.13	1.43	1.64
750	1	1.03	1.16	1.28	1.09	1.23	2.12	1.24	1.46	1.59
	2	1.03	1.13	1.28	1.14	1.34	1.87	1.14	1.46	1.71
	Av.	1.03	1.15	1.28	1.12	1.28	2.00	1.19	1.46	1.65
1000	1	1.04	1.18	1.35	1.15	1.30	2.14	1.27	1.46	1.59
	2	1.03	1.19	1.35	1.16	1.44	2.04	1.20	1.46	1.71
	Av.	1.03	1.19	1.35	1.15	1.37	2.09	1.23	1.46	1.65

Table 25. Compaction and Shear Strain Properties of Gravel Mixtures - Gyratory Compactibility Index (GCI_{50}^{x})

Number of Revolutions	Specimen Number	Grading A % Asphalt			Grading B % Asphalt			Grading C % Asphalt		
		4.7	5.0	5.3	4.7	5.0	5.3	4.7	5.0	5.3
50	1	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
	2	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
	Av.	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
100	1	.994	.994	.992	.994	.993	.994	.993	.994	.995
	2	.992	.992	.992	.994	.993	.992	.992	.994	.995
	Av.	.993	.993	.992	.994	.993	.993	.992	.994	.995
200	1	.986	.986	.984	.986	.987	.986	.986	.987	.991
	2	.984	.984	.984	.985	.985	.984	.986	.986	.990
	Av.	.985	.985	.984	.985	.986	.985	.986	.987	.991
300	1	.981	.979	.979	.981	.982	.981	.982	.983	.989
	2	.979	.978	.980	.980	.980	.979	.981	.983	.988
	Av.	.980	.978	.980	.981	.981	.980	.982	.983	.988
500	1	.976	.973	.972	.976	.975	.980	.977	.980	.987
	2	.973	.973	.974	.975	.973	.974	.977	.978	.986
	Av.	.975	.973	.973	.976	.974	.977	.977	.979	.986
750	1	.971	.968	.966	.971	.971	.975	.974	.976	.984
	2	.967	.968	.970	.969	.968	.970	.975	.975	.983
	Av.	.969	.968	.968	.970	.969	.972	.974	.975	.984
1000	1	.967	.964	.962	.967	.966	.971	.971	.974	.982
	2	.963	.965	.967	.965	.963	.967	.972	.972	.982
	Av.	.965	.964	.964	.966	.965	.969	.972	.973	.982

APPENDIX C

STATISTICAL RESULTS

Table 26. Newman-Keuls Sequential Range Test Results for Limestone Mixture Properties at 500 Revolutions - Unit Weight (Total Mix)

GRADATION

Ranked order of means		Ranked means
1	Gradation C	142.589
2	Gradation B	138.833
3	Gradation A	136.381

TABLE OF DIFFERENCES BETWEEN MEANS

Rank	3	2
1	6.208**	3.756**
2	2.452*	

% ASPHALT

Ranked order of means		Ranked means
1	% Asphalt 6.3	140.423
2	% Asphalt 6.0	139.789
3	% Asphalt 5.7	137.591

TABLE OF DIFFERENCES BETWEEN MEANS

Rank	3	2
1	2.832*	0.633
2	2.199	

* Significant at 5 percent level

** Significant at 1 percent level

Table 27. Newman-Keuls Sequential Range Test Results for Limestone Mixture Properties at 500 Revolutions - Unit Weight (Aggregate Only)

GRADATION

Ranked order of means		Ranked means
1	Gradation C	134.515
2	Gradation B	130.971
3	Gradation A	128.661

TABLE OF DIFFERENCES BETWEEN MEANS

Rank	3	2
1	5.854**	3.544**
2	2.310*	

% ASPHALT

Ranked order of means		Ranked means
1	% Asphalt 6.3	132.100
2	% Asphalt 6.0	131.877
3	% Asphalt 5.7	130.171

TABLE OF DIFFERENCES BETWEEN MEANS

Rank	3	2
1	1.929	0.224
2	1.706	

* Significant at 5 percent level

** Significant at 1 percent level

Table 28. Newman-Keuls Sequential Range Test Results for Limestone Mixture Properties at 500 Revolutions - Gyratory Stability Index (GSI^{X}_{50})

GRADATION

Ranked order of means			Ranked means
1	Gradation	C	1.150
2	Gradation	B	1.059
3	Gradation	A	1.033

TABLE OF DIFFERENCES BETWEEN MEANS

Rank	3	2
1	.117*	.091*
2	.026	

% ASPHALT

Ranked order of means			Ranked means
1	% Asphalt	6.3	1.133
2	% Asphalt	6.0	1.075
3	% Asphalt	5.7	1.034

TABLE OF DIFFERENCES BETWEEN MEANS

Rank	3	2
1	.099	.059
2	.041	

* Significant at 5 percent level

** Significant at 1 percent level

Table 29. Newman-Keuls Sequential Range Test Results for Limestone Mixture Properties at 500 Revolutions - Gyratory Compactibility Index (GCI^x_{50})

GRADATION

	Ranked order of means	Ranked means
1	Gradation B	.963
2	Gradation C	.962
3	Gradation A	.955

TABLE OF DIFFERENCES BETWEEN MEANS

Rank	3	2
1	.008	.001
2	.007	

% ASPHALT

	Ranked order of means	Ranked means
1	% Asphalt 5.7	.964
2	% Asphalt 6.0	.959
3	% Asphalt 6.3	.957

TABLE OF DIFFERENCES BETWEEN MEANS

Rank	3	2
1	.007	.005
2	.002	

* Significant at 5 percent level

** Significant at 1 percent level

Table 30. Newman-Keuls Sequential Range Test Results for Limestone Mixture Properties at 1000 Revolutions - Unit Weight (Total Mix)

GRADATION

Ranked order of means		Ranked means
1	Gradation C	144.212
2	Gradation B	140.729
3	Gradation A	138.378

TABLE OF DIFFERENCES BETWEEN MEANS

Rank	3	2
1	5.834**	3.483**
2	2.351*	

% ASPHALT

Ranked order of means		Ranked means
1	% Asphalt 6.3	142.430
2	% Asphalt 6.0	141.549
3	% Asphalt 5.7	139.341

TABLE OF DIFFERENCES BETWEEN MEANS

Rank	3	2
1	3.089*	.881
2	2.208*	

* Significant at 5 percent level

** Significant at 1 percent level

Table 31. Newman-Keuls Sequential Range Test Results for Limestone Mixture Properties at 1000 Revolutions - Unit Weight (Aggregate Only)

GRADATION

Ranked order of means		Ranked means
1	Gradation C	136.047
2	Gradation B	132.760
3	Gradation A	130.545

TABLE OF DIFFERENCES BETWEEN MEANS

Rank	3	2
1	5.502**	3.287**
2	2.215*	

% ASPHALT

Ranked order of means		Ranked means
1	% Asphalt 6.3	133.988
2	% Asphalt 6.0	133.537
3	% Asphalt 5.7	131.827

TABLE OF DIFFERENCES BETWEEN MEANS

Rank	3	2
1	2.161	.451
2	1.710	

* Significant at 5 percent level

** Significant at 1 percent level

Table 32. Newman-Keuls Sequential Range Test Results for Limestone Mixture Properties at 1000 Revolutions - Gyratory Shear.

% ASPHALT

Ranked order of means		Ranked means
1 % Asphalt	5.7	26.940
2 % Asphalt	6.0	26.094
3 % Asphalt	6.3	25.458

TABLE OF DIFFERENCES BETWEEN MEANS

Rank	3	2
1	1.482	.846
2	.636	

* Significant at 5 percent level

** Significant at 1 percent level

Table 33. Newman-Keuls Sequential Range Test Results for Limestone Mixture Properties at 1000 Revolutions - Gyratory Stability Index (GSI^{x}_{50})

GRADATION

Ranked order of means			Ranked means
1	Gradation	C	1.352
2	Gradation	B	1.136
3	Gradation	A	1.086

TABLE OF DIFFERENCES BETWEEN MEANS

Rank	3	2
1	.266**	.216**
2	.050	

% ASPHALT

Ranked order of means			Ranked means
1	% Asphalt	6.3	1.302
2	% Asphalt	6.0	1.177
3	% Asphalt	5.7	1.095

TABLE OF DIFFERENCES BETWEEN MEANS

Rank	3	2
1	.207*	.125*
2	.082	

* Significant at 5 percent level

** Significant at 1 percent level

Table 34. Newman-Keuls Sequential Range Test Results for Limestone Mixture Properties at 1000 Revolutions - Gyratory Compactibility Index (GCI_{50}^{x})

GRADATION

Ranked order of means		Ranked means
1	Gradation C	.951
2	Gradation B	.950
3	Gradation A	.942

TABLE OF DIFFERENCES BETWEEN MEANS

Rank	3	2
1	.009	.001
2	.008	

% ASPHALT

Ranked order of means		Ranked means
1	% Asphalt 5.7	.952
2	% Asphalt 6.0	.947
3	% Asphalt 6.3	.944

TABLE OF DIFFERENCES BETWEEN MEANS

Rank	3	2
1	.008	.005
2	.003	

* Significant at 5 percent level

** Significant at 1 percent level

Table 35. Newman-Keuls Sequential Range Test Results for Gravel Mixture Properties at 500 Revolutions - Unit Weight (Total Mix)

GRADATION

Ranked order of means		Ranked means
1	Gradation C	152.163
2	Gradation B	151.118
3	Gradation A	147.684

TABLE OF DIFFERENCES BETWEEN MEANS

Rank	3	2
1	4.479**	1.045
2	3.434**	

% ASPHALT

Ranked order of means		Ranked means
1	% Asphalt 5.3	150.710
2	% Asphalt 5.0	150.603
3	% Asphalt 4.7	149.651

TABLE OF DIFFERENCES BETWEEN MEANS

Rank	3	2
1	1.060	.107
2	.953	

* Significant at 5 percent level

** Significant at 1 percent level

Table 36. Newman-Keuls Sequential Range Test Results for Gravel Mixture Properties at 500 Revolutions - Unit Weight (Aggregate Only)

GRADATION

Ranked order of means		Ranked means
1	Gradation C	144.918
2	Gradation B	143.921
3	Gradation A	140.650

TABLE OF DIFFERENCES BETWEEN MEANS

Rank	3	2
1	4.268**	.998
2	3.270**	

* Significant at 5 percent level

** Significant at 1 percent level

Table 37. Newman-Keuls Sequential Range Test Results for Gravel Mixture Properties at 500 Revolutions - Gyratory Shear

	Ranked order of means		Ranked Means
	Gradation	% Asphalt	
1	C	4.7	28.378
2	A	4.7	27.645
3	B	4.7	27.106
4	A	5.0	26.972
5	A	5.3	26.512
6	B	5.0	26.496
7	B	5.3	25.038
8	C	5.0	24.800
9	C	5.3	23.833

TABLE OF DIFFERENCES BETWEEN MEANS

Rank	9	8	7	6	5	4	3	2
1	4.545**	3.578**	3.340**	1.882**	1.866**	1.406**	1.272**	.733**
2	3.812**	2.845**	2.607**	1.149**	1.133**	.673*	.539*	
3	3.273**	2.306**	2.068**	.610	.594	.134		
4	3.139**	2.172**	1.934**	.476	.460			
5	2.679**	1.712**	1.474**	.016				
6	2.663**	1.696**	1.458**					
7	1.205**	.238						
8	.967**							

* Significant at 5 percent level

** Significant at 1 percent level

Table 38. Newman-Keuls Sequential Range Test Results for Gravel Mixture Properties at 500 Revolutions - Gyratory Stability Index (GSI^{x}_{50})

	Ranked order of means		Ranked Means
	Gradation	% Asphalt	
1	C	5.3	1.639
2	B	5.3	1.631
3	C	5.0	1.430
4	A	5.3	1.247
5	B	5.0	1.195
6	C	4.7	1.127
7	A	5.0	1.094
8	B	4.7	1.087
9	A	4.7	1.015

TABLE OF DIFFERENCES BETWEEN MEANS

Rank	9	8	7	6	5	4	3	2
1	.624**	.552**	.545**	.512**	.444**	.392**	.209**	.008
2	.616**	.544**	.537**	.504**	.436**	.384**	.201**	
3	.415**	.343**	.336**	.303**	.235**	.183**		
4	.232**	.160	.153	.120	.052			
5	.180*	.108	.101	.068				
6	.112	.040	.033					
7	.079	.007						
8	.072							

* Significant at 5 percent level

** Significant at 1 percent level

Table 39. Newman-Keuls Sequential Range Test Results for Gravel Mixture Properties at 500 Revolutions - Gyratory Compactibility Index (GCI^{x}_{50})

	Ranked order of means		Ranked Means
	Gradation	% Asphalt	
1	C	5.3	.986
2	C	5.0	.979
3	B	5.3	.977
4	C	4.7	.977
5	B	4.7	.976
6	A	4.7	.975
7	B	5.0	.974
8	A	5.0	.973
9	A	5.3	.973

TABLE OF DIFFERENCES BETWEEN MEANS

Rank	9	8	7	6	5	4	3	2
1	.013**	.013**	.012**	.011**	.010**	.009**	.009**	.007**
2	.006	.006	.005	.004	.003	.002	.002	
3	.004	.004	.003	.002	.001	.000		
4	.004	.004	.003	.002	.001			
5	.003	.003	.002	.001				
6	.002	.002	.001					
7	.001	.001						
8	.000							

* Significant at 5 percent level

** Significant at 1 percent level

Table 40. Newman-Keuls Sequential Range Test Results for Gravel Mixture Properties at 1000 Revolutions - Unit Weight (Total Mix)

GRADATION

Ranked order of means			Ranked means
1	Gradation	C	152.917
2	Gradation	B	152.530
3	Gradation	A	149.090

TABLE OF DIFFERENCES BETWEEN MEANS

Rank	3	2
1	3.827**	.387
2	3.440**	

* Significant at 5 percent level

** Significant at 1 percent level

Table 41. Newman-Keuls Sequential Range Test Results For Gravel Mixture Properties at 1000 Revolutions - Unit Weight (Aggregate Only)

GRADATION

Ranked order of means			Ranked means
1	Gradation	C	145.636
2	Gradation	B	145.266
3	Gradation	A	141.990

TABLE OF DIFFERENCES BETWEEN MEANS

Rank	3	2
1	3.646**	.370
2	3.276**	

* Significant at 5 percent level

** Significant at 1 percent level

Table 42. Newman-Keuls Sequential Range Test Results for Gravel Mixture Properties at 1000 Revolutions - Gyratory Shear

	Ranked order of means		Ranked Means
	Gradation	% Asphalt	
1	A	4.7	27.692
2	C	4.7	27.355
3	B	4.7	26.908
4	A	5.0	26.760
5	B	5.0	26.285
6	A	5.3	25.727
7	C	5.0	23.880
8	C	5.3	23.363
9	B	5.3	22.407

TABLE OF DIFFERENCES BETWEEN MEANS

Rank	9	8	7	6	5	4	3	2
1	5.285**	4.329**	3.812**	1.965**	1.407**	.932*	.784*	.337
2	4.948**	3.992**	3.475**	1.628**	1.070**	.595	.447	
3	4.501**	3.545**	3.028**	1.181**	.623	.148		
4	4.353**	3.397**	2.880**	1.033**	.475			
5	3.878**	2.922**	2.405**	.558				
6	3.320**	2.364**	1.847**					
7	1.473**	.517						
8	.956**							

* Significant at 5 percent level

** Significant at 1 percent level

Table 43. Newman-Keuls Sequential Range Test Results for Gravel Mixture Properties at 1000 Revolutions - Gyratory Stability Index (GSI^{x}_{50})

	Ranked order of means		Ranked Means
	Gradation	% Asphalt	
1	B	5.3	2.093
2	C	5.3	1.649
3	C	5.0	1.463
4	B	5.0	1.368
5	A	5.3	1.351
6	C	4.7	1.235
7	A	5.0	1.187
8	B	4.7	1.035
9	A	4.7	

TABLE OF DIFFERENCES BETWEEN MEANS

Rank	9	8	7	6	5	4	3	2
1	1.058**	.938**	.906**	.858**	.742**	.725**	.630**	.444**
2	.614**	.494**	.462**	.414**	.298**	.281**	.186**	
3	.428**	.308**	.276**	.228	.112	.095		
4	.333**	.213*	.181	.133	.017			
5	.316**	.196*	.164	.116				
6	.200*	.080	.048					
7	.152*	.032						
8	.120							

* Significant at 5 percent level

** Significant at 1 percent level

Table 44. Newman-Keuls Sequential Range Test Results for Gravel Mixture Properties at 1000 Revolutions - Gyratory Compactibility Index (GCI^{x}_{50})

	Ranked order of means		Ranked Means
	Gradation	% Asphalt	
1	C	5.3	.982
2	C	5.0	.973
3	C	4.7	.972
4	B	5.3	.969
5	B	4.7	.966
6	A	4.7	.965
7	B	5.0	.964
8	A	5.0	.964
9	A	5.3	

TABLE OF DIFFERENCES BETWEEN MEANS

Rank	9	8	7	6	5	4	3	2
1	.018**	.018**	.017**	.017**	.016**	.013**	.010**	.009**
2	.009*	.009*	.008*	.008*	.007*	.004	.001	
3	.008*	.008*	.007	.007	.006	.003		
4	.005	.005	.004	.004	.003			
5	.002	.002	.001	.001				
6	.001	.001	.000					
7	.001	.001						
8	.000							

* Significant at 5 percent level

** Significant at 1 percent level